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A. A. CHEKANOV

WELDING OF METALS UNDER LOW (CONDITIONS OF) SURROUNDING TEMPERATURES

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This book is devoted to problems in the welding of metals under low surrounding temperatures. The effect of low temperatures upon the properties of metals and welded seams is reviewed. The specific characteristics of the welding process under low temperature conditions are described. Investigation and research data pertaining to welding bonds effected in surrounding sub-zero weather is cited.

It is intended for the use of engineers and technicians engaged in the welding industry.

INTRODUCTORY NOTE

The welding of metals under low surrounding temperatures constitutes a serious problem for the national economy of the Soviet Union. In the construction of industrial projects in the northern areas of the USSR, in the construction of ships, in repair and restoration work, etc., welding is frequently done under temperatures considerably below zero Centigrade. However, no clear directions for the industrial technology of welding under such climatic conditions is available as yet.

The existence in the Soviet Union of vast areas, where long winters prevail, make the problem of cold weather welding a very actual one.

In the Institutes for Science and Research in the USSR (Institute of Electric Welding, Academy of Sciences, Ukrainian SSR, imeni Academician E. O. Paton, and in the Leningrad Polytechnical Institute, the chair of N. N. Davidenkov), and in the plant laboratories, a series of scientific investigations was conducted with the object of studying the behavior of welded items, which are called upon to perform under low temperatures.

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In welded objects made from most varieties of steel, the ultimate strength and fatigue limit become higher with lower operating temperatures, while plastic deformation under static loads varies comparatively little.

The impact ductility of the basic metal, as well as of the welded joints, drops sharply with the lowering of the test temperatures.

Improvements in the technology of welding led to considerably higher mechanical properties in welded structures which were called upon to stand up under low temperatures. The successful operation under low temperatures of welded structures in railway rolling stock, motor cars, airplanes, structural installations (reservoirs, metallurgical equipment, hoisting, conveying and transportation equipment) has been going on for many years in the USSR.

However, the problems of conducting welding operations under conditions of frost, what is the effect of freezing temperatures on the welding process, and how the welded objects (made under conditions of freezing) will stand up under subsequent operation and service, still remain to be solved.

Numerous experiments conducted in the MVTU (Moscow Higher Technical ~~School College~~) welding laboratory imeni Bauman, show a variance between the operational and the technological strength. There are many examples on record, where the welded objects possess high mechanical properties under normal operating conditions, yet in the very process of welding they show a tendency to brittle rupturing.

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The investigations conducted in this laboratory by A. A. Chekanov, aimed at the study of both the technological and operational properties of joints that are welded under conditions of frost.

The thorough and resourceful experiments by A. A. Chekanov promoted the clarification of this exceptionally important problem. Comrade Chekanov has demonstrated that welding under frost conditions does not change the operational properties of welded structures. The ultimate strength, the yield point, the relative elongation, the impact ductility, the welding deformation, and other indexes for structures that are welded under frost conditions, are not substantially different from the same indexes obtained in welding done at room temperature.

The results of the experiments conducted by A. A. Chekanov, Candidate in Technical Sciences, make it possible to recommend to the industries [concerned], that no limitations be set on the temperatures under which welding operations may be conducted, and utilize the welding processes under any temperature conditions, insuring, however, all the basic conditions which the operation of welding requires.

The following problems are discussed in this book: (1) the effect of low temperatures on the welding process and on the properties of welded joints which are made under low temperature conditions; (2) the effect of low temperatures on the mechanical properties of welded joints made under conditions of positive temperatures.

These problems are of particular interest to ship building welders, since in the ship building installations, during the winter,

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welding operations take place in open stages and dockyards. They are also of interest to welders making welded constructions that are operated at low temperatures.

Many plants comprising metal constructions are located in areas, where the temperature of the air during the winter drops to minus 40 degrees Centigrade. This is a case where the constructions are both welded and maintained under low temperature conditions.

The effect of low operating temperatures on plastic and brittle ruptures in welded constructions has as yet been investigated only to a small degree, and must become the subject of research and study in the next few years.

Chapter 1

THE EFFECT OF LOW TEMPERATURES ON THE PROPERTIES OF METALS

As is known, considerable variations in mechanical properties occur at low temperatures in ferrous alloys, while in non-ferrous metal alloys, under the same conditions, the respective variations are of a smaller degree.

The mechanical properties of metals subject to the effect of low temperatures, can be broken down into these 3 groups:

(1) Static strength;

(2) Vibrationary /dynamic/ strength;

(3) Impact ductility

I. STATIC STRENGTH

The ultimate strength, elasticity and ductility, as well as

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the hardness of steels, are increased with a reduction in temperature, in a ratio depending on its chemical composition and the type of heat treatment it received.

Relative elongation and relative reduction in area, in response to a reduction in temperature, will sometimes increase, sometimes decrease, and sometimes remain stationary.

A. S. Fal'kerich (1) and others established the fact that, in the case of ferrous alloys, all characteristics of static strength increase with low temperatures.

1. Carbon- and Low Alloy-Steels

Data on the variations in the properties of carbon- and low-alloy steels, at various temperatures and under the effect of static loads, is depicted in Table 1.(2)

It shows that at minus 183 degrees Centigrade the ultimate strength is increased 1.5-2 times, and hardness is increased 1.5 times.

The various components of the steel exert various effects on the mechanical strength of the alloy at low temperatures. As for instance, a higher carbon content increases the ultimate strength and the yield point of the steel.

The properties of a metal at low temperatures are greatly affected by the heat treatment it received. Investigations (2) have shown that when carbon- and low alloy-steels are hardened and tempered in oil, their plasticity characteristics will be much higher than same for annealed steels (see Table 2).

I. V. Kudryavtsev of TsNIITMASH(3) [Central Scientific Research Institute for ~~Heavy~~ Machine Building Technology and] investigated the mechanical properties

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of brand St. 3 rolled carbon steel at low temperatures (down to minus 70 degrees Centigrade).

Bessemer steel from the Kerch' and Dneproderzhinsk Plants and open-hearth steel from the Novo-Saldinsk, Magnitogorsk, and imeni Voroshilov Plants, were tested. The open-hearth steel had a carbon content 2-3 times higher than the Bessemer steel, but a lower content of sulfur, oxygen, nitrogen, and phosphorus.

The results of testing these steels at minus 70 degrees Centigrade show that the ultimate strength, the yield point, hardness, and relative elongation, all increase with the reduction in temperature.

Below is a tabulation of the mechanical properties, variations sustained by rolled carbon steel in the temperature interval from plus 20 to minus 70 degrees Centigrade.

Mechanical Properties	Increment in Percent (under above Conditions)
Ultimate Strength	20.5
Yield Point	42.5
Relative Elongation	12.8

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THE EFFECT OF LOW TEMPERATURES ON THE MECHANICAL PROPERT

MATERIAL	CHEMICAL COMPOSITION IN PERCENT								MECHANICAL PROPERTI						
									+20 degrees Centigrade				-80 degrees		Ce
	C	Si	Mn	P	S	Cr	Ni	Mo	Ultimate Strength Kilograms per Square Millimeter	Elastic Limit Kilograms per Square Millimeter	Elongation in Percent	Reduction of Area in Percent	Ultimate Strength Kilograms per Square Millimeter	Elastic Limit Kilograms per Square Millimeter	Elongation in
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(1
Electrolytic iron	--	--	--	--	--	--	--	--	30	16	46	--	33	23	4
Carbon Steel A(Kirov Plant) 15	0.11	traces	0.35	0.16	0.022	0.14	0.39	--	37.8	28.1	30	70.6	45.3	36.9	3
Carbon Steel B (Kirov Plant) 40 G	0.39	0.33	0.73	0.041	--	0.1	--	--	48.9	31.4	27.2	65	54.8	39.5	2
Carbon Steel	0.32	0.27	0.63	0.037	0.016	--	--	--	59	35	28	--	--	--	.
Chromo-Molybdenum Steel (20 KLM)	0.22	03.3	0.6	0.015	0.005	0.83	0.09	0.22	76	61.3	19.1	69	80.1	63.8	2
Chromo-Molybdenum Steel	0.36	0.25	0.83	0.015	0.004	1.12	0.15	0.25	34	68.5	22.3	70	--	--	-
Chromo-Molybdenum Steel	0.43	0.35	0.66	0.014	0.005	1.02	0.08	0.22	108	93.8	17.3	61	--	--	-

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TABLE I

...W TEMPERATURES ON THE MECHANICAL PROPERTIES OF CARBON AND LOW ALLOY STEELS

...MECHANICAL PROPERTIES AT TEMPERATURES											Brinell Hardness at Temperatures	
...ees Centigrade			-80 degrees Centigrade				-183 degrees Centigrade					
...Square Millimeter	Elongation in Percent	Reduction of Area in Percent	Ultimate Strength Kilograms per Square Millimeter	Elastic Limit Kilograms per Square Millimeter	Elongation in Percent	Reduction of Area in Percent	Ultimate Strength Kilograms per Square Millimeter	Elastic Limit Kilograms per Square Millimeter	Elongation in Percent	Reduction of Area in Percent	+20 degrees Centigrade	-183 degrees Centigrade
...)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
...5	46	--	33	23	45	--	63	58	16	--	--	--
...1	30	70.6	45.3	36.9	33.3	75.4	82.2	--	2.8	0.6	--	--
...4	27.2	65	54.8	39.5	28.4	55.3	--	--	--	--	--	--
...5	28	--	--	--	--	--	93	71	26	--	160	265
...3	19.1	69	80.1	63.8	22.5	69	111.2	103.8	18	41	229	323
...5	22.3	70	--	--	--	--	128.2	117.2	21.9	47	234	356
...8	17.3	61	--	--	--	--	146.7	139.4	15.8	44	282	409

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(1
Chromium-Molybdenum Vanadium Steel (0.19 percent Vanadium)	0.31	0.29	0.67	0.01	0.006	2.36	--	0.24	122.2	110.2	15	63	132.8	122.9	14
Chromium-Nickel-Molybdenum Steel	0.34	0.27	0.45	0.012	0.009	1.88	2.27	0.4	117.8	104.3	16.7	65	127.7	115.4	17.2
Chromium-Nickel Steel	0.12	0.28	0.39	0.017	0.014	1.0	2.26	--	80.3	76.8	12.5	73.9	--	--	--

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(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
15	63	132.8	122.9	14.4	58	161.9	152.4	14	37	350	453
16.7	65	127.7	115.4	17.2	63	158.4	142.6	19.1	52	337	411
12.5	73.9	--	--	--	--	113.1	110.6	20.2	62	203	303

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) (12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
2 15	63	132.8	122.9	14.4	58	161.9	152.4	14	37	350	453
3 16.7	65	127.7	115.4	17.2	63	158.4	142.6	19.1	52	337	411
12.5	73.9	--	--	--	--	113.1	110.6	20.2	62	203	303

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THE EFFECT OF HEAT-TREATMENT ON THE PR

Grade of Steel	C	Mn	Si	P	S	Ni	Cr	Heat Treatment	Mechanical Properties at +20 degrees Centigrade: Yield Point in Kilograms per Square Millimeter	Ultimate Strength in Kilograms per Square Millimeter	Elongation in Percent	Reduction in Area in Percent
Carbon	0.40-50	0.60-0.90	0.15-0.30	0.045	0.055	--	--	Annealing at 815 degrees Centigrade. Hardening in oil at 815 degrees Centigrade, and tempering at 588 degrees Centigrade.	35	62.6	29	48
									54	73	26	67
Nickel	0.35-0.45	0.60-0.90	0.15-0.30	0.040	0.045	3.25-3.75	--	Annealing at 788 degrees Centigrade. Hardening at 843 degrees Centigrade in oil, and Tempering at 649 degrees Centigrade.	38.7	74.6	21	44
									53.4	71.7	18	45
Chromium-nickel	0.34-0.40	0.30-0.60	-0.15-0.30	0.040	0.050	1.5-2.0	0.90-1.25	Annealing at 788 degrees Centigrade. Hardening in oil at 788 degrees Centigrade, and tempering at 621 degrees Centigrade	527	82.3	24.5	62.0
									81.6	92.8	21	60

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TABLE II

EFFECT OF HEAT-TREATMENT ON THE PROPERTIES OF STEEL (AT LOW TEMPERATURES)

Mechanical Properties AT Temperatures +20 degrees Centigrade				-190 degrees Centigrade			
Yield Point in Kilograms per Square Millimeter	Ultimate Strength in Kilograms per Square Millimeter	Elongation in Percent	Reduction in Area in Percent	Yield Point in Kilograms per Square Millimeter	Ultimate Strength in Kilograms per Square Millimeter	Elongation in Percent	Reduction in area (in percent)
35	62.6	29	48	90	97	3.8	3.6
54	73	26	67	105	112	9.9	9.4
38.7	74.6	21	44	69.6	90.7	2.5	2.8
53.4	71.7	18	45	62.6	90	3.3	3.7
527	82.3	24.5	62.0	92.8	120.9	14.3	13.1
81.6	92.8	21	60	118.8	131.8	19.0	30.0

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2.Alloy Steels of the Austenitic Type

The ultimate strength, the elastic limit, the yield point, and the hardness of austenitic steels, all become higher with a reduction in temperature. Austenitic steels, such as Nickel steels, containing more than 13 percent Nickel, austenitic chromo-manganese steels with a 9-18 percent manganese content, Hatfield steels, austenitic chrome-nickel steels with an 18-25 percent chromium content and an 8-24 percent nickel content (stainless steels of the grades EYa-1, EYa-2, and others), were tested in order to establish the above.

In stainless chrome-nickel steel, the elastic limit and the yield point increase in proportion to the temperature variations, while the ultimate strength, in the temperature range of plus 15 to minus 80 degrees Centigrade, increases more rapidly than at temperatures below this range.

Steels with a total of 28 percent chromium and nickel content, at a temperature of minus 185 degrees Centigrade, fully retain their austenitic structure, and show a relative elongation up to 50 percent (see Table 3).

3.Non-Ferrous Metals

A. B. Fradkov (2) cites data to the effect that, with reduction in temperature, almost all the indexes for the mechanical properties of non-ferrous metals and their alloys show an increase (see Table 4).

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TABLE III

VARIATIONS IN THE MECHANICAL PROPERTIES OF AUSTENITIC ALLOY STEELS AT LOW TEMPERATURES

Steel	Chemical Composition in Percent		Mechanical Properties at Temperature + 20 degrees Centigrade: Ultimate Strength in Kilograms per Square Millimeter	Elastic Limit in Kilograms per Square Millimeter	Relative Elongation in Percent	Reduction in area in Percent	Mechanical Properties at Temperature -183 degrees Centigrade: Ultimate Strength in Kilograms per Square Millimeter	Elastic Limit in Kilograms per Square Millimeter	Relative Elongation in Percent	Reduction in area in Percent	Brinell Hardness at temperature- +20 (degrees	Brinell Hardness at temperature- -183 Centigrade)
Austenitic	C = 0.57, Si = 0.31,	Mn= 6.88 Ni = 13.00	72.2	35.5	81.8	76	109.9	59.9	46.0	48	184	227
Austenitic	C = 0.04, Si = 0.02,	Mn = 0.28 Ni = 85.18	52.5	42.5	27.6	72	90.5	64.0	31.6	61	144	220
Austenitic	C = 0.12, Si = 0.24,	Mn = 0.94 Ni = 42.06	57.4	35.5	35.5	70	92.5	51.6	40.9	62	153	205
Type 18-8 Austenitic Chromium-Nickel	C = 0.12, Si = 0.43,	Cr = 18.8 Ni = 8.1	74	40**	56	53.5	185*	86*	25*	30.5	175	---

*At minus 255 degrees Centigrade.

** Yield point.

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VARIATIONS IN THE MECHANICAL PROPERTIES OF NON-FERROUS METALS AND ALLOYS AT LOW

Metal	Chemical Composition in percent					Mechanical Properties at Tem								
						+ 15 degrees Centigrade				-80 degrees Centigrade				
	Cu	Zn	Pb	Fe	Al	Ultimate strength in Kilograms per square millimeter	Elastic limit in kilograms per square millimeter	Relative elongation in percent	Reduction in area in percent	Ultimate strength in kilograms per square millimeter	Elastic limit in kilograms per square millimeter	Relative elongation in percent	Reduction in area in percent	Ultimate
Copper	99.9	--	--	--	--	27.9	8.8	13.3	71.5	36.7	10.0	22.9	65.3	
Electrolytic C opper	99.96	--	--	--	--	22.5	--	55.3	74	--	--	--	--	
Rolled Brass	58.9	38.7	1.5	--	--	42.4	20*	25.7	--	--	--	--	--	
Annealed Brass	6.0	38.4	1.1	0.5	--	40.0	11.6*	39	--	--	--	--	--	57.
Cast Bronze	82.5	17.5	--	--	--	28	13*	32	36.7	--	--	--	--	31.
Rolled Bronze	--	--	--	--	--	43.3	40*	36	65.4	--	--	--	--	65.
Delta-Metal (cast)	57.1	40.7	0.7 Manga-nese	0.9	--	36.7	--	22.3	--	--	--	--	--	
Duralu-min	4.32	0.42 Silicon	0.50 Manga-nese	0.01	92.63	41.1	18.1	19.7	41.8	43.3	17.9	24.5	37	53.

* Yield Point

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METALS AND ALLOYS AT LOW TEMPERATURES

TABLE IV

ical Properties at Temperatures

Centigrade			-180 degrees Centigrade				BRINNEL HARDNESS AT TEMPERATURE	
Relative elongation in percent	Reduction in area in percent	Ultimate strength in kilograms per square millimeter	Elastic limit in kilograms per square millimeter	Relative elongation in percent	Reduction in area in percent	+ 15 degrees Centigrade	-180 degrees Centigrade
22.9	65.3	41.3	41.3	12.7	30.7	67.9	--
--	--	35.7	--	63.5	76	84	105
--	--	58.0	20.98*	36.0	--	94	124
--	--	57.0	17.0*	41.0	--	--	--
--	--	31.8	21.5*	15.3	24.6	--	--
--	--	65.5	50.5*	56.3	58	--	--
--	--	--	--	--	--	94	113
24.5	37	53.3	25.1	13.3	18.7	--	--

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II. DYNAMIC STRENGTH

Under low temperature conditions, structures frequently have to sustain /dynamic/ loads containing a reversal of sign. Therefore, the problem of fatigue in metals at low temperatures assumes particular significance. As yet, little research has been done in this field.

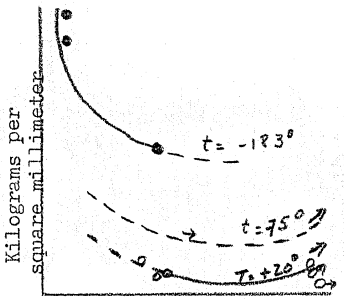

Figure 1. Curves characterizing fatigue in E-8 steel, work-tested under various temperatures.

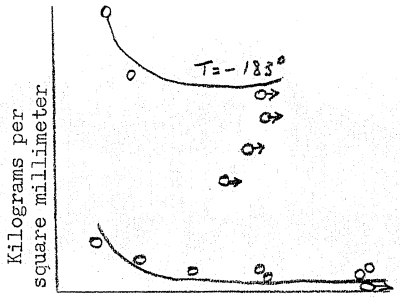

Figure 1a. Curves characterizing fatigue in St. 3 steel tested under temperatures ranging from plus 20 degrees to minus 183 degrees Centigrade.

As a rule, the value of the fatigue limit of ferrous metals under a cycle of symmetric loads is approximately half the value of its ultimate tensile strength. The fatigue limit, as well as the ultimate strength, is increased with the reduction in temperature.

I. V. Kudryavtsev and V. S. Chernyak (4) investigated the resistivity of E-8 and St. 3 steels to fatigue at low temperatures, with the results presented in Table 5 and Figure 1.

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TABLE V

Grade and Chemical Composition of steel (in percent)	Ultimate Fatigue in Kilograms per square millimeter		Increase in strength with reduction in temperature from + 20 degrees Centigrade to -183 degrees Centigrade in percents of:		
	At +20 degrees Centigrade	At -183 degrees centigrade	Yield point	Ultimate tensile strength	Ultimate Fatigue
E - 8 steel C = 0.34 Mn = 0.40 Si = 0.27 S = 0.008 P = 0.037 Cr = 1.3 Ni = 3.28	39.0	56.0	67.0	47.8	48.7
St. 3 steel C = 0.15 Mn = 0.51 Si = 0.088 S = 0.018 P = 0.061	22.0	50.5	128.0	80.9	130.0

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The examination of specimens was conducted, in contrast with the cumbersome and expensive machinery and models used abroad, in a special machine designed for TsNIITMASH by I. V. Kudryavtsev (5). The test was effected by dipping the specimens into a bath filled with a refrigerating liquid.

The machine constructed by TsNIITMASH makes it possible to conduct the fatigue test with a stationary specimen in a liquid refrigerating medium. As a result of these tests, the deduction was made that the operation of steel parts subject to /dynamic/ loads containing a reversal of sign at low temperatures, is permissible. The break which occurred at minus 183 degrees Centigrade was coarse-grained-brittle. The formation of fatigue cracks immediately induces a brittle break through the entire cross section of the specimen.

III. IMPACT DUCTILITY

With a reduction in temperature, the impact ductility of steels is reduced.

1. Carbon and Low Alloy Steels.

The reduction in impact ductility at low temperatures is usually so considerable that the metal becomes brittle, and loses its ability to resist dynamic loads. Therefore, the value of the impact ductility is the basic characteristic for metal which is to stand up under low temperatures.

Impact ductility at low temperatures in low alloy steels, particularly chromium-nickel and chrome-molybdenum steels, is higher than the same in carbon steels at equal temperatures.

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The value of impact ductility at low temperatures depends on the chemical composition of the steel. The higher the carbon content, the less the impact ductility. Nickel, copper, vanadium, molybdenum, manganese (within certain limits), and chromium increase the impact ductility of steel.

Molybdenum has a benevolent effect on the steel, when it enters into its composition together with nickel, chromium, or with both of these. The greatest increase in the impact ductility of steel is induced by its nickel content, even though it may be small.

The basic criterion for the reliability of metal in structures operating at low temperatures, is its impact ductility test, the absolute values of which decrease with a decrease in temperature.

Impact ductility at low temperatures is lower for Bessemer steel (3) than for open-hearth steel, which is due to the higher content of sulfur and phosphorus in the Bessemer steel. Therefore, it is best to use open-hearth steel in the northern areas for important construction called upon to sustain dynamic loads.

Heat treatment tends to increase the impact ductility of steel at low temperatures. In addition to heat treatment, the percentage of carbon content, the degree of deoxidation of the metal, the purity of the after-charge materials, and the absence in the welded construction of its own stresses, also affect the impact ductility of carbon steels.

V. V. Kurayev and V. G. Chernashkin (6) plotted graphs (Figure 2) showing the relation between impact ductility and temperature for various steels. As can be seen from these graphs, the impact ductility of low-carbon steel, within the temperature range of plus 5 to minus

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20 degrees Centigrade, may be reduced from 12 to 2 kilograms/square centimeter.

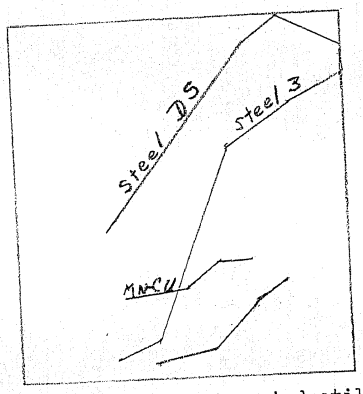

Figure 2. Relation between the impact ductility of various steels and temperature (Kurayev and Chernashkin)

When carbon steels are not deoxidized in smelting, they retain an adequately high impact ductility only down to temperatures from minus 20 to minus 40 degrees Centigrade. Deoxidation with aluminum or silicon results in high impact ductility down to the temperature of minus 70 and even minus 78 degrees.

N. F. Bolokhvitinov (7) notes that the grain structure of the steel has a tremendous effect upon its impact ductility. In fine-grained steels, impact ductility is much higher, particularly at low temperatures (minus 20 and minus 40 degrees Centigrade). Therefore, fine grained steel is recommended for constructions subject to winter-time impact loads.

Alloy steels, particularly chromium-nickel steels, retain their impact ductility at low temperatures to a greater degree than carbon steels.

Many specialists point out that the admixture of nickel to

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steel, under any type of heat treatment and any percentage of carbon content, will improve the properties of the steel at low temperatures. According to some data, the admixture of vanadium and molybdenum is even more desirable.

Some high alloy steels retain their impact ductility at low temperatures to a considerably higher degree than carbon steels. For example, chrome-molybdenum steel of the formula C = 0.4 percent, Cr = 17.68 percent, Mo = 1.8 percent, retains an impact ductility of 1.3 kilogram/square centimeter even at minus 195 degrees Centigrade.

2. Alloy Steels of the Austenitic Type

Although the impact ductility of alloy steels of the austenitic type is reduced with the reduction in temperature, its value is adequately high even at minus 183 degrees Centigrade. Therefore, austenitic steels are fully suitable for constructions operating at low temperatures. For example, the impact ductility of steels with a total chromium-nickel content up to 28 percent, at minus 183 degrees Centigrade, has an impact ductility of 17-20 kilograms/square centimeter.

Even a higher impact ductility, at the above low temperature (up to 24 kilograms/square centimeter), is characteristic of chromium-manganese steels of the following chemical composition: carbon 0.11-0.13 percent, silicon 0.40-0.47 percent, chromium 14.2-15.6 percent, nickel 0.80-1.08 percent, and manganese 15.5 to 16.4 percent.

Specimens of austenitic steels tested for tensile strength at low temperatures show cup-shaped and conical forms of rupture, which testifies to the high plasticity of these steels at low temperatures.

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Carbon and low-carbon steels, as a rule, show brittle ruptures under low temperature conditions.

Table 6 contains data on the value of impact ductility of austenitic alloy steels at low temperatures.

Table 6. Impact Ductility of Austenitic Steels.

Steel	Chemical Composition (in percent)	Impact Ductility in kilogram/square Centimeter	
		at plus 20 degrees Centigrade	at minus 185 degrees Centigrade.
Austenitic Nickel	C = 0.57, Mn = 6.88, Si = 0.31, Ni = 13.0	39.2	15
Austenitic Nickel	C = 0.04, Mn = 0.29, Si = 0.02, Ni = 85.18	21.5	14
Austenitic Nickel	C = 0.12, Cr = 0.94, Si = 0.24, Ni = 42.06	22.7	25
Austenitic Chromium-Nickel (Type 18-8)	C = 0.12, Cr = 18.8 Si = 0.43, Ni = 8.1	20-21	17-20

3. Non-Ferrous Metals.

The impact ductility of non-ferrous metals is reduced little with reduction in temperature, and, in the case of some metals, such as copper and aluminum, at minus 180 degrees Centigrade, it is even increased 1.5 times as compared to the impact ductility at room temperature. Therefore, non-ferrous metals are widely used in structures operating at low temperatures.

The impact ductility of lead (as tested on the Charpy impact machine), is 2.3 kilogram/square centimeter at room temperature, 3.7

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kilogram/square centimeter at minus 183 degrees Centigrade, and 4.4 kilogram/square centimeter at minus 225 degrees Centigrade.

From the above data follows:

(1) The ultimate strength and the elastic limit, also the hardness of steels, are increased with the reduction in temperature by a value related to the chemical composition and the heat treatment of the steels.

The impact ductility of steels is decreased with the reduction in temperature.

(2) In the case of non-ferrous metals, almost all mechanical properties are increased with a reduction of temperature. Impact ductility is decreased very little, and, in the case of copper and aluminum, it becomes even higher.

IV. METHODS FOR THE TESTING OF METALS AT LOW TEMPERATURES

Properly selected methods of testing are of the utmost importance in ascertaining the performance of metals at low temperatures. It must be noted that no unified system for these tests exists, and individual researchers follow individual practices. Conventional machinery for testing the properties of metals may easily be adapted to low temperature testing.

The low temperatures required for the tests are produced by the following methods:

(1) By cooling the compartment containing the testing machine to the required test temperature. This method, the conditions for

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which are not always easily accomplishable, furnishes the best means for insuring a homogeneous temperature throughout the test.

(2) By locating the specimens to be tested and the adjacent part of the testing machine in an insulated container, into which a refrigerating medium is led prior to the beginning of the tests, with additions introduced into the container during the test, as needed.

(3) By cooling the specimens in a proper medium and carrying them rapidly to the testing machine. This is a convenient method for short-range tests, such as impact tests. The specimen is refrigerated to a temperature somewhat below that required by the test, in order to compensate for the temperature gain sustained by the specimen during the carrying interval and during the test itself. The carrying tongs and the clamping device are to be refrigerated to the same temperature as the specimen.

As a refrigerant for the obtaining of the low temperatures required by the test, the following can be used:

for minus 20 degrees Centigrade -- a brine solution;

for minus 80 degrees Centigrade -- solid carbon dioxide, acetone, alcohol, or ester compounds;

for minus 150 degrees Centigrade -- liquid air and ester compounds, or liquid propane;

for minus 183 degrees Centigrade -- liquid air;

for minus 253 degrees Centigrade -- liquid hydrogen.

The low temperatures are read with the aid of liquid thermometers made of glass (toluene thermometers for temperatures down to minus 65 degrees Centigrade), or thermocouples (iron-constantan or copper-constantan).

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V. I. Voznyak (8) maintains that during the impact test the specimen is in the open air for not longer than 10 seconds, during which its temperature is increased by 2 degrees Centigrade. This may be compensated by super-cooling the specimen by 2 degrees with relation to the fixed test temperature.

In refrigerating to minus 80 degrees Centigrade, the following liquid refrigerants, with a low solidification temperature, are used for the bath: acetone, methyl alcohol, toluene, etc. Lumps of solid carbon dioxide are dipped into the bath to bring the temperature down to the required level.

Still lower temperatures, such as minus 200 degrees Centigrade, are attained with the aid of liquid air. In these cases, the temperatures are easily controllable.

Chapter II

THE EFFECT OF LOW TEMPERATURES ON THE PROPERTIES OF WELDED JOINTS MADE UNDER CONDITIONS OF NORMAL TEMPERATURE

Results of investigations on the performance of welded joints at low temperatures lead to the assumption that variations in their properties are analogous to the variations in the properties of the basic metals.

The review of the research available, as in the preceding chapter, may be divided as follows:

(1) Static strength;
(2) Dynamic strength;
(3) Impact Ductility.

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I. STATIC STRENGTH

Numerous investigations of Soviet researchers have shown that with a reduction in the temperature of the welded seams, their yield point, elastic limit, ultimate strength, and hardness are increased.

1. Carbon Steels

(a) Electric Arc-Welding

The laboratory of the First Autogenous Welding Plant in collaboration with the Research Institute for General Machine Building (9) conducted experiments in electric arc welding on St. 3 steel. The results are depicted in Table 7.

Table 7. Properties of Electric Arc-Welded Joints (St. 3-Steel)

Specimens	Mechanical Properties: Ultimate Strength in kg/mm^2 at Temperatures		Yield Point in kg/mm^2 at Temperatures	
	20 C	-183 C	20 C	-183 C
Basic Metal	43.9	55.4	32.2	43.7
Weld Metal	41.8	45.4	--	--

The welding was done with a 170-210 amperes AC electric current, and 4 millimeter electrodes with OMM-5 coating were used.

A. S. Fal'kerich (10) conducted experiments with St. 5-steel. The results are shown in Table 8.

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Table 8. Properties of Electric Arc-Welded Joints (St. 5-Steel)

Specimen	Mechanical Properties			
	Ultimate Strength in kg/mm^2 at Temperatures		Brinell Hardness at Temperatures	
	20 C	-183 C	20 C	-183 C
Welded Seam	42.1	65.7	144	234
Weld Metal	40.7	51.9	---	---

Experiments by V. S. Chernyak (11) for ascertaining the strength of A. C. electric arc-welded seams, in low carbon steels, have shown that the ultimate strength is increased from 48 kilograms/square millimeter at plus 20 degrees Centigrade to 55 kilograms/square millimeter at minus 60 degrees Centigrade. Four-millimeter electrodes with a coating composition consisting of 23 percent field spar, 24.7 percent of iron oxide, the balance being ferro-manganese and chalk. The current was of 170-210 amperes.

(b) Gas Welding

V. S. Chernyak conducted experiments with the welding of low carbon steels by means of an oxyacetylene flame, and established the fact that, with a reduction in temperature, the ultimate strength of the above steel is increased.

2. Austenitic Steels

Chromium-Nickel austenitic steels, as already mentioned, possess high mechanical properties at low temperatures.

V. S. Chernyak, Z. I. Golubeva, and I. A. Shteynberg (12), in the laboratory of the First Autogenous Welding Plant, investigated

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the mechanical properties of welded seams in chromium-nickel EYaIT (18-8) Steel.

The composition of the basic metal, admixed metal, and the deposited metal is given in Table 9.

Table 9. Composition of the Metal in Welding of EyaIT steel.

Specimen	Chemical composition (in percent)			
	C	Cr	Ni	Ti
Basic Metal	0.18	18.71	10.8	0.6
Admixed	0.12	12.47	10.2	0.82
Deposited Metal	0.15	17.52	10.2	0.49

Stainless chromium-nickel EYaIT steel is used in manufacturing equipment which is called upon to sustain extremely low temperatures. It is, therefore, important to know the behavior of welded seams in this metal.

In testing specimens of the basic metal, the following results were obtained (Table 10).

Table 10. Results of Tests Made on EYaIT steel at Various Temperatures.

Temperature in Degrees Centigrade	Mechanical Properties	
	Ultimate Strength in kg/mm^2	Relative Elongation in Percent
Plus 20	76.03	47.24
Minus 40	94.04	42.5
Minus 75	113.12	38.94
Minus 183	162.41	33.77

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For the testing of welding seams 8 millimeter plates were welded by D. C. electric current at reversed polarity. TsL-2 electrodes, recommended by the welding laboratory of TsNIITMASH for the welding of 18-8 steels, were used. The welding was done at normal temperature, with 4 millimeter electrodes and 160 ampere current. Results relating to the determination of the mechanical properties of the deposited metal at various temperatures are shown in Table 11.

Table 11. Results of Testing Welded Specimen of EYaIT Steel.

Temperature in degrees Centigrade	Mechanical Properties	
	Ultimate Strength in kg/mm^2	Relative Elongation in Percent
Plus 20	68.7	36.8
Minus 40	89.0	31.5
Minus 75	90.9	29
Minus 183	109.6	18.6

It can be seen from Table 11 that even the minimum value for relative elongation at minus 183 degrees Centigrade meets the specifications required for pressure tanks.

In tensile strength tests, EYaIT steels form recesses, and the rupture has a fine-grained structure, which is not the case in carbon steels.

Results of testing welded seams show (at least at temperatures down to minus 40 degrees Centigrade) that the properties of the seams are close to those of the basic metal.

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The sharp reduction in plasticity within the range from minus 60 degrees Centigrade to minus 183 degrees Centigrade is due to the non-homogeneity of the deposited metal, the presence of carbide inclusions, and also to the partial transformation of austenite into martensite. Carbide inclusions are present in all the layers of the deposited metal. The results of these tests are presented /graphically/ in Figure 3.

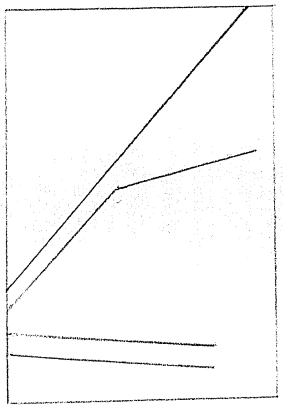

Figure 3. Results of Elongation Tests on the Basic and Deposited Metals (EYaIT Steel).

Legend: 1 - Ultimate strength of the basic metal;
2 - Ultimate strength of the deposited metal;
3 - relative elongation of the basic metal;
4 - relative elongation of the deposited metal.

As a rule, the values for the ultimate strength, plasticity, and yield point at low temperatures, obtained for the welded seams and the basic metal in austenitic chromium-nickel steels, are rather close to each other.

The quality of seams made by metal electrode welding are superior to that of gas welded seams of the same steel.

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The results of tests on welded joints in 18-8 chromium-nickel steel at low temperatures, have shown that this steel, by its mechanical properties, is entirely suitable for use under conditions of extremely low temperatures. It does not sustain the sharp reduction in relative elongation, so characteristic of carbon steels in the range from plus 20 degrees Centigrade to minus 183 degrees Centigrade. The relative elongation of this steel at minus 183 degrees Centigrade is only 25 percent less than at normal temperature.

3. Non-Ferrous Metals

The study of the properties of welded seams in non-ferrous metals at low temperatures is of great practical interest, inasmuch as non-ferrous metal welding, at the present time, is applied on a large scale in equipment operating at extremely low temperatures. The mechanical properties of welded seams in copper and brass at low temperatures, vary analogously with the variations of same in the basic metal.

Copper and brass gas-welded joints were tested at low temperatures at the laboratory of the First Autogenous Welding Plant. The results of these tests are presented in Table 12.

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TABLE 12

RESULTS OF TESTS ON NON-FERROUS METAL SPECIMEN

Grade, Material and Composition of Specimens (in percent)	Mechanical Properties at Temperatures			
	Ultimate strength in Kilograms per square millimeter		Relative elongation in percent	
	+20 Degrees Centigrade	-183 Degrees Centigrade	+20 Degrees Centigrade	-183 Degrees Centigrade
LZhMTs Brass (Cu = 59, Fe = 1.2, Mn = 0.62, Zn = the balance	41.9	49.8	30.4	47.5
Welded seam in 22 millimeter plate	38.5	45.7	20.8	27.0
Welded seam in 36 millimeter plate	38.2	43.8	27.2	14.8
M-3 Copper (basic metal, Cu = 95.5 percent)	23.0	25.0	30.0	31.0
Welded seam in M-3 Copper	20.4	25.7	17.3	18.8

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II. DYNAMIC STRENGTH

The laboratory of TsNIITMASH has shown that the fatigue limit in electric arc-welded joints of St. 3 steel is increased at minus 183 degrees Centigrade. Other researchers (13) concur in this deduction (see Tables 13 and 14).

The basic material in these tests was 19-21 millimeter mild steel plate of the following composition: 25 percent carbon, 0.67 percent manganese, 0.014 percent phosphorus. The welding cycle was as follows: 150 ampere 28 volt DC, reversed polarity.

L. M. Yarovinskiy and I. V. Kudryavtsev, in 1939-1940, investigated the fatigue resistance of of cast steels and weld-deposited metal at the temperature range from plus 100 degrees to minus 75 degrees Centigrade. They also investigated the effect of heat treatment on the fatigue resistance of the weld-deposited metal. The welding was done with OMM-5 electrodes, in order to eliminate defects in the cast steel automatic couplings, the side frame, and the swivel pin beam of railroad car wheel trucks. It was established that fatigue resistivity at low temperatures (down to minus 75 degrees Centigrade) is by 22-32 percent higher in the deposited metal than in the basic cast steel.

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TABLE 13

FATIGUE LIMIT IN WELDED SEAMS OF LOW CARBON STEEL AT LOW TEMPERATURES

Specimen and Welding method	Fatigue limit in kilograms per square millimeter at temperature					
	+20 degrees Centigrade	0 degrees Centigrade	-20 degrees Centigrade	-40 degrees Centigrade	-60 degrees Centigrade	-70 degrees Centigrade
Basic Metal	21.6	22.2	22.5	24.6	25.0	26.0
Contact butt-weld	19.0	19.6	20.2	21.5	21.9	22.2
Quality electrode arc-weld	18.5	19.4	20.0	20.5	21.0	21.2

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TABLE 14

FATIGUE LIMIT IN WELDED SEAMS OF 18 - 8 STEEL AT LOW TEMPERATURES

Specimen and Welding Method	Fatigue limit in kilograms per square millimeter at temperature					
	+20 degrees Centigrade	0 degrees Centigrade	-20 degrees Centigrade	-40 degrees Centigrade	-60 degrees Centigrade	-70 degrees Centigrade
Basic Metal (18-8 Steel)	41.5	42	44.6	41.4	43.2	43.5
Arc welding (4 millimeter electrode 125 amperes, 24 volt current, 19 millimeter plate)	43	43.4	45	42	43	44

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Thus, the feasibility of rectifying cast steel rejects by quality electrode arc welding of steel parts, designed to operate under dynamic loads containing a change of sign, and under low temperature conditions, was established.

III. IMPACT DUCTILITY

As already mentioned above, low temperatures exert a negative effect on the impact ductility of metals. Therefore, in determining the effect of low temperatures on the mechanical properties of welded joints, the determination of impact ductility is of basic importance.

Many varieties of welded joints are cold-brittle, and impact tests are made in order to determine the degree of this brittleness.

In the impact testing of welded joints at low temperatures, the following factors are of great importance, and the effect of each is to be determined: carbon content, method of deoxidation, structural grain size, shape and location of break, nitrogen content, and the type of heat treatment.

1. Carbon and Low Alloy Steels.

A series of tests have established that impact ductility at low temperatures runs in an inverse ratio to the carbon content of the steel, i.e. the higher the carbon content, the lower the impact ductility at low temperatures.

The testing of two pairs of steel plates (0.13 percent carbon in the first pair, and 0.42 percent in the second), oxyacetylene butt-welded, respectively, established the fact that the impact ductility in the welded seam of the first pair of plates, within the

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temperature range of plus 20 to minus 50 degrees Centigrade, is about twice as high as in the welded seam of the second pair. The steel with the 0.42 percent carbon content, already at the plus 20 degrees temperature, shows very low absolute values for impact ductility in the welded seams (less than 3 kilogram/square centimeter). For satisfactory impact ductility values at low temperatures, steel with a carbon content not to exceed 0.30 percent, is to be used.

At temperatures below minus 50 degrees Centigrade, the value of the impact ductility of the basic metal and the welded seams is small, and the metal is in a state of brittleness, which will increase with the increase in carbon content.

Proof was furnished by tests that, given a definite carbon content, impact ductility at low temperatures will vary in direct ratio to the degree of dispersion of carbide /inclusions/.

V. I. Voznyak (15) determined the low temperature impact ductility in welded joints made by various welding methods, with results shown in Table 15.

/See next page for Table 15/

The data depicted in Table 15 shows that the impact ductility of the deposited metal is always below that of the basic metal. The impact ductility of welded seams in low carbon steel at low temperatures has an insignificant value, and at minus 50 degrees Centigrade it is only 0.1-0.4 kilogram/square centimeter.

The absolute values for impact ductility of electrically welded joints of low carbon structural steel are higher than those of electrically welded conventional low carbon steel.

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TABLE 15

Metal and Welding Method	Impact ductility in kilograms per square centimeter at temperature			
	-50 degrees Centigrade	-25 degrees Centigrade	0 Degrees Centigrade	+20 degrees Centigrade
Basic Metal (St. 2 Steel)	0.47	17.25	24.08	23.2
Welded Seams:				
AC current, chalk-coated electrodes	0.125	0.25	1.0	0.81
Heavily-coated electrodes	0.37	1.49	8.44	11.0
DC current, chalk-coated electrodes	0.12	0.12	0.22	0.52
Contact welding	--	1.93	8.5	--
Oxy-acetylene welding	0.32	0.256	0.61	3.15

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The values for the impact ductility of welded seams in low carbon steel, when austenitic electrodes are used in the welding, are given below:

Temperature in degrees Centigrade	Impact Ductility in kg/cm^2
Plus 18	7.9
0	7.4
Minus 10	7.12
Minus 20	6.0
Minus 30	5.6
Minus 40	5.1
Minus 50	4.2

In the welding laboratory of the MVTU /the Moscow Technical College/ imeni Bauman, N. N. Prokhorov and I. I. Makarov (16), under the guidance of Prof. G. A. Nikolayev, investigated the weldability of 3 M low carbon steel with a cuprous admixture of the following chemical composition: carbon 0.14-0.15 percent, silicon 0.02 percent, manganese 0.46-0.56 percent, sulfur 0.020-0.055 percent, phosphorus 0.018-0.053 percent, copper 0.16-0.25 percent.

The determination of the mechanical and technological properties of welded seams was conducted on standard specimens for impact ductility tests within the range of plus 20 and minus 40 degrees Centigrade. The specimens were welded with the aid of UONI-13 and OMM-5 electrodes; also, automatic-welded under a layer of flux.

The results of mechanical tests on such welded joints are given in Table 16.

/Table 16 on next page/

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TABLE 16

RESULTS OF MECHANICAL TESTS ON WELDED SEAMS IN CUPROUS STEEL

Welding Method and Electrode Grade	Ultimate Strength in Kilograms per Square Millimeter	Impact Ductility in Kilograms per Square Centimeter		Angle of bead (in degrees)
		at -20 degrees Centigrade	at -40 degrees Centigrade	
Manual, CHM-5 electrodes	43.5	12.1	7.2	43
Manual, UONI-13 electrodes	42.8	12.5	7.0	42
Automatic, under layer of flux	43.4	14.0	7.57	115

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For welding joints which are to operate at low temperatures, electrodes made from austenitic steels, less sensitive to low temperatures, are sometimes used.

Welding with austenitic electrodes results in seams of high mechanical properties, which, in turn, accounts for the ever wider use of such electrodes.

The testing of the austenitic electrode-welded joints were conducted by A. P. Tulyakov [17] on a steel of the following composition: carbon 0.12 percent, silicon 0.01 percent, manganese 0.39 percent, phosphorus 0.007 percent, and sulfur 0.016 percent. The chemical composition of the electrodes is given in Table 17.

[Table 17 on next page]

The electrodes used were heavily coated. There were less alloying admixtures in the deposited metal than in the electrode metal.

The results of testing austenitic electrode-welded seams in low carbon steel are given in Table 18.

[Table 18 on page 457]

Austenitic electrode welding results in welded seams with adequately high ductility at low temperatures. In welding structures designed to operate at temperatures down to minus 80 degrees Centigrade, the use of electrodes made from chromium-nickel steel (20 percent chromium and 20 percent nickel) and chromium-manganese steel (15 percent, chromium, 17 percent manganese and up to 0.2 percent carbon) is recommended.

Welded seams effected with chromium-nickel steel electrodes

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TABLE 17

COMPOSITION OF STEEL IN AUSTENITIC ELECTRODES

Grade of Steel	Chemical composition in percent				
	C	Si	Mn	Cr	N_i
Chromium-Nickel 20/40	0.44	--	1.35	20.45	39.32
Chromium-Nickel 20/20	0.11	0.85	--	20.54	20.21
Chromium-Manganese 15/10	0.2	0.92	9.01	16.37	--
Chromium-Manganese 14/20	0.2	0.95	17.02	14.2	--

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TABLE 18

RESULTS OF TESTS ON WELDED SEAMS MADE WITH AUSTENITIC ELECTRODES

Electrode Specification	Impact ductility in kilograms per square centimeter at temperature			
	+15 degrees Centigrade	-40 degrees Centigrade	-80 degrees Centigrade	-180 degrees Centigrade
Steel 20/40	10.1	5.3	10.3	2.6
Coating No 23	0.2	3.5	8.9	--
Steel 20/20	11.6	9.5	9.9	5.8
Coating no 23	5.4	5.0	6.2*	3.3*
Steel 15/20	7.2	4.1*	2.8	0.7
Coating of dolomite type	6.7	3.3*	2.7	0.2

*Specimens showed blistering in breaks.

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have an impact ductility of 5.8-7.2 kilograms per square centimeter at minus 183 degrees Centigrade. When the less expensive chromium-manganese steel electrodes are used, the results are satisfactory only down to minus 80 degrees Centigrade, with an impact ductility, at this temperature, of 3 kilograms/square centimeter.

2. Alloy Steels.

Low carbon chromium-cuprous steels, without heat-treatment or normalizing, have an adequate impact ductility at low temperatures, and may be welded without fear of air-hardening.

Low temperature experiments (12) for impact ductility in welded seams of EYaIT (18-8) chromium-nickel steel, were conducted by the laboratory of the First Autogenous Welding Plant.

The composition of the basic, admixed, and deposited metal was given in the preceding text (in Table 9). Eight-millimeter plates were welded by DC current, at reversed polarity. Electrodes with TsL-2 coating were used. The results of impact tests on EYaIT steel are given in Table 19.

/For Table 19 see next page/

In Figure 4, this relationship is presented graphically.

/For Figure 4 see next page/

Based on these investigations, the deduction can be made that EYaIT steel is fully suitable for low temperature welding. The ultimate strength of this steel begins to rise at as low a temperature as minus 40 degrees Centigrade, the impact ductility of the basic

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TABLE 19

IMPACT DUCTILITY IN WELDED SPECIMENS OF EYaIT STEEL

Specimens	Impact ductility in kilograms per square centimeters at temperature			
	-20 degrees Centigrade	-40 degrees Centigrade	-75 degrees Centigrade	-183 degrees Centigrade
Basic metal	29.2	30.9	32.6	29.4
Welded Seam	15.35	13.6	12.36	6.85

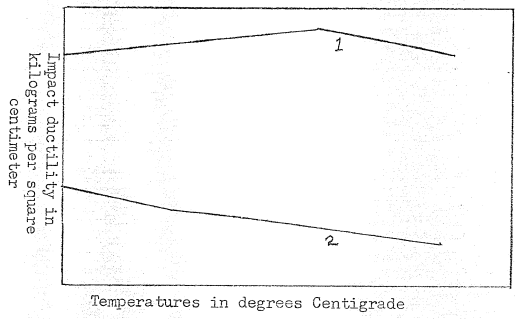

Figure 4. Results of the impact ductility test for basic metal and welded seam (EYaIT Steel)

Line 1 - basic metal; Line 2 - welded seam

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metal does not change with the reduction in temperature, and the impact ductility of the welded seam, at minus 183 degrees Centigrade, is reduced by 50 percent as compared with same at room temperature. The deposited metal insures the formation of an austenitic structure in the metal of the welded seam.

Determination of the impact ductility of the welded seam in austenitic chrome-manganese-molybdenum steel (C = 0.17 percent, Si = 0.23 percent, Mn = 12 percent, Cr = 14.57 percent, Mo = 1.42 percent) was conducted by A. P. Tulyakov. The welding was done with heavily coated electrodes. A part of the specimens, prior to testing, was subjected to heat treatment (water-quenched to the hardening temperature of 1150 degrees Centigrade). Results are given in Table 20.

/See next page for Table 20/

The above Table shows that, with the reduction in temperature, the ductility of the welded seam decreases sharply. Therefore, when the above grade of steel is used in low temperature operation, it becomes necessary to develop the technology of welding by determining the welding cycle, the pre-heating of parts, etc.

In the testing (18) of welded seams in chromium-nickel steel (chrome 24.66 percent, nickel 19.25 percent, manganese 1.15 percent, silicon 1.4 percent), the impact ductility of the basic metal and the welded seam showed variations in a ratio to temperature as presented graphically in Figure 5.

/See page 50 for Figure 5/

The graph shows that at minus 50 degrees Centigrade, the welded

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TABLE 20

IMPACT DUCTILITY OF WELDED SPECIMENS OF CHROME-MANGANESE-MOLYBDENUM STEEL

Specimens	Heat treatment	+15 degrees Centigrade	-40 degrees Centigrade	-80 degrees Centigrade	-180 degrees Centigrade
Basic metal	without	5.4	6.5	8.37	10.65
Welded seam	without	4.8	2.52	2.87	0.77
Basic metal	Hardening at 1150 degrees Centigrade	37.8	36.5	37.3	36.2
Welded seam	Hardening at 1150 degrees Centigrade	5.81	8.35	6.4	2.07

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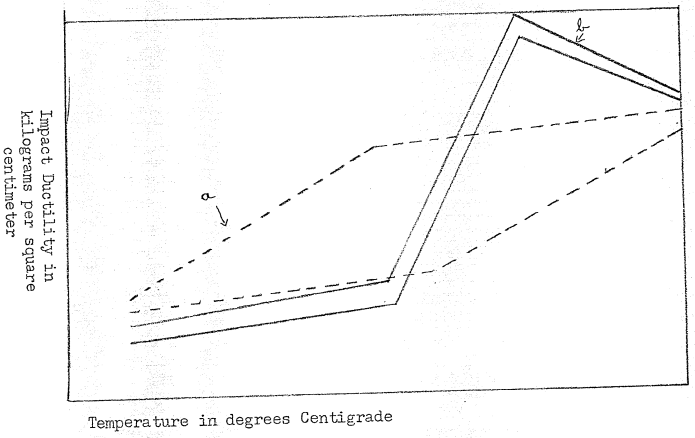

Figure 5. Impact ductility of chromium-nickel steel (Cr=24.64 percent, Ni=19.25 percent) at various temperatures.

Line a - basic metal; line b - welded seam

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seam has a high impact ductility, in excess of same for the basic metal. With further reduction in temperature, the impact ductility of the seam is sharply reduced, with a value of 10.5 kilograms/square centimeter at minus 100 degrees Centigrade, and 9.5 kilograms/square centimeter at minus 195 degrees Centigrade.

The decrease in the impact ductility of the basic metal is more gradual, to the effect, that for the temperature range from plus 20 degrees Centigrade to minus 100 degrees Centigrade it is decreased only by 1.5 kilograms/square centimeter. At minus 195 degrees Centigrade, the basic metal has an impact ductility, which is equal to the impact ductility of the welded seam at minus 100 degrees Centigrade.

Prof. G. A. Nikolayev (19) also underscores the fact that welded structures made of nickel steels retain adequate impact ductility at low temperatures, provided special electrodes are used in the welding operation.

V. D. Taran (20) made impact ductility tests on welded seams in St. 3 steel, and found that, with reduction in temperature, impact ductility is decreased, with a state of full brittleness at minus 30-minus 40 degrees Centigrade.

The Institute of Electric Welding, Academy of Sciences, Ukranian SSR, and the Ordzhonikidzegrad Institute of Machine Building (21) experimented with specimens of weld deposits on several varieties of wire, welded by an open arc under a layer of flux. The results are given in Table 21.

/See page following for Table 21/

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TABLE 21

RESULTS OF IMPACT DUCTILITY TESTS WITH SPECIMENS OF WELD DEPOSITS

Grade of wire, coating and flux	-80 degrees Centigrade	-60 degrees Centigrade	-40 degrees Centigrade	-20 degrees Centigrade	0 degrees Centigrade	10 degrees Centigrade	20 degrees Centigrade
Silico-manganese wire with AN - 1 coating	--	--	5.0	9.8	--	12.5	--
Low carbon wire with AN - L coating	--	--	4.5	7.4	8.5	--	10.8
Silicon wire (welding under KP -7 flux)	1.4	3.2	5.3	--	8.8	--	9.7

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G. I. Pogodin-Alekseyev makes the following deduction: the transition of the weld deposit metal from a ductile to a brittle state begins even at room temperature. However, even at minus 40 degrees Centigrade, the metal still has an adequate impact ductility (approximately, 5 kilograms/square centimeter). Complete brittleness develops at minus 80 degrees Centigrade.

3. Non-Ferrous Metals

V. S. Chernyak also conducted impact ductility tests on welded specimens of copper and brass. Grade M-3 copper plate, 8-10 millimeters thick, and Grade LMZh ferro-manganese brass plate, 22-36 millimeters thick, were used as the base metal. As welding rod in the welding of the copper plate, electrolytic copper rods were used of 3 by 4 millimeter rectangular cross-section, and in the welding of the brass plate - 5 millimeter diameter brass rods.

In both cases, the welding was by oxyacetylene flame, with the use of special fluxes.

The tests demonstrated that, with a reduction in temperature, the impact ductility of welded seams in copper is increased, while, in the case of brass, it remains unchanged.

This data is depicted in Table 22.

/See next page for Table 22/

The impact ductility curve for welded seams in aluminum, with relation to low temperatures, is presented graphically in Figure 6.

/See next page for Figure 6/

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TABLE 22

IMPACT DUCTILITY OF WELDED COPPER AND BRASS

Material	Impact ductility in kilograms per square Centimeter at temperature	
	-20 degrees Centigrade	-183 degrees Centigrade
Copper (basic metal)	9.1	11.0
Copper (Welded seam)	9.45	10.4
Brass (basic metal)	11.98	9.8
Brass (Welded seam in 22 millimeter plates)	10.7	11.6
Brass (Welded seam in 32 millimeter plates)	6.9	8.5
Brass (Welded seam in 36 millimeter plates)	10.6	9.8

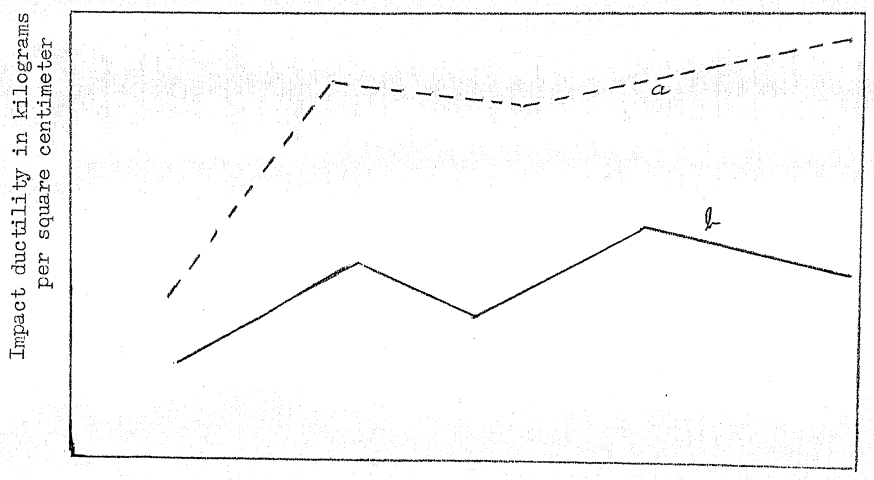

Figure 6. The effect of low temperatures on the impact ductility of welded seams in aluminum.

Line a - basic metal; line b - welded seam.

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Data on the impact ductility of welded seams in silumin is shown in Table 23.

[See page 56 for Table 23]

The impact ductility of welded seams in Monel metal was also investigated. A sheet 9 millimeters thick was electric arc butt-welded. The impact ductility of the welded specimen at plus 20 degrees Centigrade was 10.76 kilograms/square centimeter, at minus 190 degrees Centigrade it was 10.07 kilograms/square centimeter, i.e. practically constant within the above temperature range.

In high-grade welding, the impact ductility of the deposited metal, at low temperatures, may equal or exceed that in the basic metal.

K. V. Lyubavskiy (22) established that the impact ductility of low carbon steel, automatic-welded under OSTs-45 flux, is, at low temperatures, higher than same for the basic metal (see Figure 7).

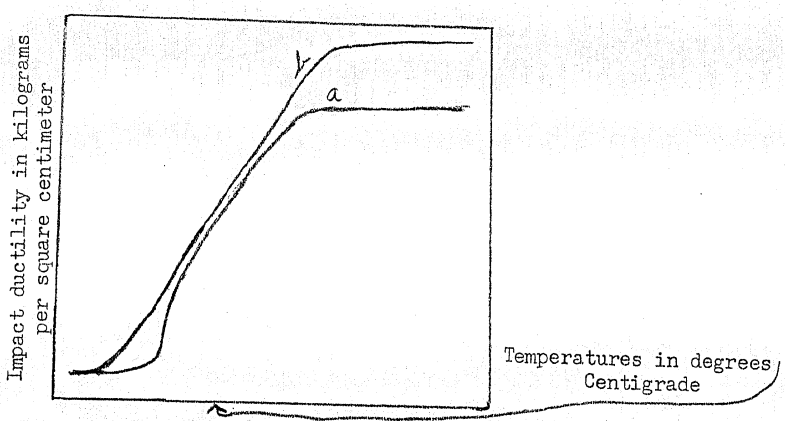

Figure 7. Impact ductility - temperature curves (a - for the basic metal, b - for the welded specimen). Low carbon wire automatic-welded, with the use of OSTs-45 flux.

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TABLE 23

IMPACT DUCTILITY OF WELDED SEAMS OF SILUMIN

Specimen	Impact ductility in kilograms per square centimeter at temperatures						
	-20 degrees Centigrade	0 degrees Centigrade	-20 degrees Centigrade	-40 degrees Centigrade	-70 degrees Centigrade	-120 degrees Centigrade	-195 degrees Centigrade
Basic metal	1.57	1.62	1.7	1.65	1.44	1.22	1.04
Welded seam (without heat treatment)	0.73	1.4	1.45	1.36	1.3	1.18	0.99

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All the above cited data on the testing of welded seams at low temperatures, lead to the deduction that, with a reduction in temperature, variations in the properties of welded seams in steels and non-ferrous metals are analogous to the variations in the properties of the basic metals. In the case of steels, the reduction in temperatures brings a decrease in impact ductility values, while, at the same time, their static characteristics (ultimate strength, elastic limit, also hardness) are increased. The impact ductility of welded seams in copper and aluminum is increased with the reduction in temperatures, while, under the same conditions, the impact ductility of welded seams in brass, silumin and Monel metal, for all practical purposes, remains constant.

Chapter III

WELDING UNDER LOW SURROUNDING TEMPERATURES

I. FORMATION OF CRACKS IN WELDED JOINTS

The evolution, in the process of welding, of volumetric variations which induce the appearance in the welded structure of internal stresses and residual deformations, is due to the thermal expansion of the metal in the heated part. As a result of this expansion, there is the appearance in the work piece of temporary temperature stresses leading to plastic deformations, and sometimes to the development of cracks.

At the present time, there are several theories with relation to the causes of crack formation during the welding operation.

MVTU [The Moscow Technical College] imeni Bauman, represented

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by G. A. Nikolayev and N. N. Prokhorov, and also A. A. Alov [23] are of the opinion that the causes for the formation of cracks are due to the presence in the welded joints and in the heat affected zones of internal stresses, induced by the rapid and concentrated heating and cooling, which in turn are tied in with local structural transformations, expansion and shrinkage of the metal.

The evolution of cracks is induced by the formation, during the welding operation, in the heat affected zones, of structures with reduced plasticity.

As is known, there are 3 varieties of internal stresses: (1) zonal stresses which are evolved between separate zones of the cross-section; (2) intragranular stresses; (3) stresses within the elementary cell.

G. A. Nikolayev and N. N. Prokhorov [24], on the basis of numerous experiments, maintain that the principal and most frequent causes for the appearance of hot and cold cracks in welded seams, are the internal stresses of the first variety, which are generated during the welding process. The internal stresses of the second and third varieties merely increase the tendency to the development of cracks, while basically affecting the mechanical characteristics.

The authors take note of the fact that the volumetric expansion stresses induced by the actual welding operation, are considerably in excess of the permissible operating stresses.

The production of welded structures, and operating experience with them, show that cracks occur more frequently in steels subject to hardening than in low carbon steels. Internal stresses of the

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second and third varieties, which are generated during the welding in carbon and alloy steels, are the result of the appearance of hardenability structures.

Cracks are formed either in the process of welding, when the metal is hot, or shortly after the welded seam has been cooled, also at various times after the welded construction is put into operation.

Cracks are classified as hot or cold with relation to the temperature at which they develop.

Hot cracks are those developed at high temperatures (plus 1200 degrees Centigrade and above). Inasmuch as at such temperatures the internal stresses of the second and third varieties are insignificant, the appearance of hot cracks is to be ascribed to the internal stresses of the first variety, which are induced by the uneven temperature distribution in cooling, and by a sharp drop in the plasticity of the metal.

Hot cracks occur in carbon steels as well as in low carbon steels, but more frequently they occur in hardened steels.

N. N. Rykalin and L. A. Fridlyand (25), upon experimenting with the weldability of SKhL-2 steel at normal temperatures, maintained that the above steel, with its carbon content within the range of 0.16 to 0.24 percent, shows no tendency to form cracks. Big longitudinal cracks occurred in welded seams, when OMM-5 electrodes were used, while welding done with UONI-13 electrodes was not accompanied by the formation of cracks in the welded seams.

A single-pass automatic welding operation in the case of SKhL-2

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10-millimeter steel plate, under OSTs-45 or modernized ASh flux, results in greater strength and plasticity of the welding seams (as compared to results obtained by manual welding).

The geometrical dimensions of the work piece /in relation to/ the particular welding method used, also affect the development of hot cracks. Thus, in arc welding, cracks may occur more frequently when dealing with greater thicknesses in the metal being welded. The reverse is true with relation to gas welding.

The Institute of Electric Welding, Academy of Sciences, Ukranian SSR, maintains, that one of the principal causes of hot cracks is the presence in the steel of excessive sulfur and phosphorus (26).

Of great importance in the developing of hot cracks in the heat affected zone and in the deposited metal, when welding low carbon steel, is the non-homogeneous distribution of sulfur. The above Institute also maintains that the possibilities of cracking after the welded structure is put into operation are decisively affected by the cold-brittleness of the steel, and that brittle disintegration of welded structures stems not from residual stresses, but from other factors. Frequently, the most important factor is the change in the structure of the metal in the seam and in the heat affected zone. As to the residual stresses, their effect can only manifest itself when the steel being welded tends to become brittle, also when notches, or other conditions creating a local concentration of stresses, are present. It was established experimentally that the welded seam metal tends to develop hot cracks when its carbon content is above 0.14 percent, silicon content above 0.25 percent, sulfur content above 0.04 percent, and phosphorus content above 0.05 percent.

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If the steel contains over 0.20 percent carbon and over 0.25 percent silicon, the development of hot cracks is hardly avoidable. If the steel contains sulfide lines (determined by imprint as per Bauman), internal cracks develop in those spots where the melted metal of the seam comes into contact with local accumulations of sulfide compounds in the steel.

The cracks developing in welded structures under operating conditions similarly depend on the grade of the steel. In the welding of steel, structural changes occur in the zones immediately adjacent to the welded seams. The initial cold-brittleness of the metal in these zones is increased.

Experimental research, conducted by the above Institute of Electric Welding, established the fact that low carbon steel (not above 0.2 percent of carbon), with silicon not exceeding 0.25 percent deoxidized silicon and aluminum, and free from sulfide compounds, insures against the occurrence of cracks in welded structures during their preparation, as well as after they are in operation.

Prof. G. A. Nikolayev(19) maintains that the development of cracks at low temperatures may be induced by the following factors: the presence in the structure of bessemer steel with an excessive phosphorus content; low plasticity and low impact ductility of the metal in the welded seam; the presence in the structure of volumetric stresses, particularly of the kind caused by welding defects, such as non-fusion or inclusions, and the dynamic character of the loads. In welded articles made from alloy steels, cracks will not develop when the conventional forms of structures and the correct technology of the welding process are properly combined.

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V. D. Taran explains the appearance of cracks in welded seams at low temperatures by the cold-brittleness of the steel, noting that cracks in the zone of the thermal effect are tied in with the presence in this zone of martensitic or troostitic-martensitic hardenability structures. The appearance of hardenability structures in steels is primarily influenced by their carbon content.

I. A. Lipetskiy(27), who investigated the formation of cracks in the deposited metal of butt-welded joints in structural steels, with a carbon content of 0.20, 0.36, 0.45 percent of carbon respectively, with relation to the increase in the amount of sulfur and phosphorus, also confirms the effect of the chemical composition of steel on the development of cracks. These experiments demonstrated that cracks will appear in welded joints when the ratio between the manganese and the sulfur content is below 4-6. Since, in steels with 0.20, 0.36, 0.45 percent of carbon respectively, the manganese content varies within the range from 0.16 to 0.23 percent, and the critical amount of sulfur when the cracks appeared was 0.030-0.035 percent, it becomes obvious that the appearance of cracks in the deposited metal during the cooling of the welded seams is due to the sulfur in the metal of the seams in the presence of too low an amount of manganese. This tie-in is explained by the fact that the presence of manganese in specified amounts binds a considerable part of the sulfur in the form of manganese sulfide.

I. V. Kudryavtsev(28) also points to the fact that the appearance of brittle cracks in rolled steel at low temperatures (as minus 15 degrees Centigrade) is induced by the presence in the metal of sulfur and phosphorus contaminations (0.111 percent of sulfur, and 0.19 percent of phosphorus).

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K. V. Lyubavskiy[29] investigated the sulfur reactions, accompanied by the development of cracks, in welding under flux.

In summarizing the results of the above, the deduction can be made that the development of cracks is due to a series of causes, as follows:

(a) The chemical composition and the metallurgical process in the making of the steel are unsatisfactory;

(b) Brittle structures developing during the cooling of the metal in the welded seam and the heat affected zone.

(c) Stresses developing during the cooling of the metal in the welded seam, and the inadequate plasticity of the deposited metal.

The appearance of cold cracks is also tied in with internal stresses developing during the welding operation.

The formation of cracks in welded structures which occur under operating conditions and are caused by the material, technological process, and type of seam employed in the welding operation, also by the nature of the operating loads (static or dynamic), are not discussed in this thesis.

II. PRODUCTION EXPERIENCE IN WELDING UNDER CONDITIONS OF FROST

Specifications relating to the design, manufacture, and inspection of welded structures for industrial installations, which were in effect up until 1942, prohibited welding operations at the surrounding temperature of minus 20 degrees Centigrade. These limitations were caused by the technological difficulties of welding under frost conditions, and by the appearance of cracks in the basic as well as

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in the deposited metal.

According to the rules of the State /Bureau/ for Boiler Inspection, approved in 1939, the welding of Class I vessels may be done only in enclosures, at a temperature not below plus 5 degrees Centigrade, and the welding of Class II vessels in the open air at a temperature not below minus 10 degrees Centigrade, in the absence of wind and atmospheric precipitation.

In the specifications of the former Glavneftespetsstroy /Main Administration for Special Petroleum Installations/ relating to the construction of gasoline storage tanks, the permissible maximum low temperature for responsible welding was minus 15 degrees Centigrade. In the recently drawn up specifications for the construction of the Moscow gas main network, it is minus 18 degrees Centigrade.

To date, the causes for the formation of these cracks and the methods to be used in preventing them are not fully known. It may be assumed that the cracks are a result of the ultimate effect of various factors, some of which evolve only at low temperatures. Some of the factors are not tied in with the temperature surrounding the welding operation, and, in the presence of some other unfavorable conditions, they may induce cracks even though the temperature of the surrounding air is normal. The low temperatures of the surrounding air create new unfavorable factors which lead to a more frequent appearance of cracks.

However, available industrial experience and results of investigations on the weldability of steels under various conditions show that the unfavorable effect of low /surrounding/ temperatures on welding can be eliminated.

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With a proper selection of the welding technological cycle, and the coordination of the latter with the suitable conventional forms of welded joints, it is possible to produce a high-quality welded structure practically under any temperature of the surrounding air. Parallel with the improvement in the technology of welding at low /surrounding/ temperatures, special efforts are made to protect the welder from their effect by supplying him with protective (heated) overalls, and by authorizing work interruptions for purposes of warming up.

In 1943, by order of the People's Commissariat for Construction, the welding of steel structures under any negative temperature conditions was authorized. No instructions, however, were given pertaining to the technology of welding under the conditions of frost, and frequently, due to lack of experience, welding operations under low temperature conditions, were accompanied by failures. Only in those cases where technical management displayed perseverance and initiative, were the proper methods of production were attained, and structures welded under conditions of frost gave an entirely satisfactory performance. The basic defect developing in welded seams, when the welding is done under frost conditions, is the appearance of cracks.

Welding under frost conditions takes place in shipbuilding, since in the winter shipbuilding operations proceed exclusively in open-air assembly areas and yards(30). In some areas, where shipbuilding docks are located, the mean annual temperature is plus 3 degrees Centigrade, and the mean winter temperature is never above minus 20 degrees Centigrade.

As a rule, the regulations relating to the application of

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electric arc-welding in shipbuilding specify that the place where important parts are welded be protected from rain, draughts, and temperatures below minus 5 degrees Centigrade.

By American standards, the welding of thick-walled vessels under surrounding temperatures within the range from minus 10 degrees to minus 20 degrees Centigrade, must be preceded by pre-heating. When the surrounding temperature is below minus 20 degrees Centigrade, no important welding is to be done(31). There is, however, no concrete and substantiated data that would confirm the necessity for discontinuing welding operations under low surrounding temperatures.

The experience of many of our plants, which have performed important welding operations under winter conditions, establishes the complete feasibility for the conducting of welding operations under low surrounding temperatures.

The experience of various plants points to the fact that, even though the number of cracks appearing in welded structures is increased during the winter, the effect of the low temperatures upon the welded seams or the entire structures is not exclusively to blame. It is entirely possible to weld successfully under conditions of surrounding frost provided there is a carefully studied approach to, and execution of, the technological process in its relation to the sequence in the welding of the seams, particularly where rigid structures and profiles are involved. The elimination of the unfavorable effect of the cold upon the welder himself, is of equal importance.

V. P. Vologdin and K. M. Oliferenko(32) point to the fact that during the construction of self-propelled river barges, the welding

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was done under surrounding temperatures of minus 20-minus 25 degrees Centigrade with good results. The welding of the barges began in the winter, under average temperature conditions of minus 20 degrees Centigrade, and was completed in the summer with the basic metal being heated by the sun to plus 70 degrees Centigrade.

In another case, in the welding of big ship masts made from rolled cylindrical and conical shells 10-12 millimeters in thickness, the welding of the circumferential seams, done in the open air at minus 5-minus 10 degrees Centigrade, resulted in cracks in all seams. The same operation, however, performed in a warmed enclosure, gave satisfactory results.

V. D. Taran(20), in discussing welding under winter conditions, cites a few examples of the appearance of cracks which caused the destruction of the basic metal and the metal in the welded seams; this took place when the operation was conducted in a surrounding temperature within the range of minus 10-minus 30 degrees Centigrade. It was noted that the lower the surrounding temperature, the more probable the appearance of cracks. Under these conditions, cracks appear during the process of welding as well as sometime after the completion of the welding operation. The cracks appeared in the welded structures under the effect of external forces, as well as in the absence of the latter. When chalk-coated electrodes are used, the probability of cracks occurring in the seams is much greater than in cases when quality electrodes are used. This observation is confirmed by many specialists.

Frequently, the cracks appearing in the metal of the welded seam extend to the basic metal of the structure, attaining a length of from several centimeters to 2-3 meters. Cases are recorded of cracks appearing at the moment of excitation of the electric arc.

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In the winter of 1942, a great number of /gasoline storage/ tanks were fabricated in one of the oil fields. The work was done under conditions of frost (minus 20 degrees Centigrade). The vertical seams of the tanks were overlapped with rhombic cover plates. After the welding was completed, cracks appeared in the sheets beginning at the vertical seams and situated perpendicular to them. These cracks frequently appeared several hours after the welding was completed, and their appearance was accompanied by a sharp crackling sound. On the suggestion of N. S. Strelyetskiy, the vertical seams were preheated with the aid of specially constructed coal-burning heaters. The cracks were eliminated.

N. O. Okerblom(33) also recommends the use of local preheating and the application of stronger currents in order to decrease plastic tensile deformations, which are particularly obnoxious at low temperatures.

In erecting the structural steel frame for a plant building in Siberia during the winter of 1941-1942, the butt ends of the continuous cross bars of the frame were being welded with the use of OMM-5-coated electrodes. After the cover plates were welded on, longitudinal cracks appeared in the transverse seams of the horizontal sheets. The development of cracks was eliminated by reducing the number of seams in securing the cover plates at the butt-end joints.

A. S. Chesnokov records a case of crack formations in the welded seams, under conditions of frost, of the vertical insert plates at the butt-ends of No. 60 I-beams. The insert plates were of St. 5 steel. When the insert plates were made of steel with a lower carbon content, the appearance of cracks was eliminated.

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G. M. Kovel'man(34) cites cases of disintegration at low temperatures of welded structures of basic bessemer steel. He also maintains that the use of SKhLF-steel for structures to be operated under conditions of low temperatures (particularly under dynamic loads), is not practical, due to the high content of phosphorus, chromium, and silicon.

Z. Dreizenshtok(35) records the appearance of cracks in beams fabricated from basic Bessemer steel, with a phosphorus content of 0.07 percent, when welded under the conditions of Siberian winter, with the surrounding temperature as low as minus 45 degrees Centigrade.

When open-hearth steel was used, electric arc-welding with quality-coating electrodes produced entirely positive results. Of course, the welding operator must have adequate rest periods and warm, comfortable clothing.

Good results in electric arc-welding at minus 20 degrees Centigrade, and in oxyacetylene welding at minus 31 degrees Centigrade, were obtained by Koltunov(36) in the construction of a power plant in the Urals.

K. K. Mukhanov cites a case of crack formation in the welded seams during some erection work in the North in the welding of foundation plates under columns. It may be assumed that the development of such cracks is induced by the presence of internal multi-axial stresses in the rib construction of the foundation plate.

From the above cited examples, it can be seen that the appearance of cracks during welding operations conducted under frost condi-

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tions can very frequently be eliminated by the use of very simple technological counter-measures such as pre-heating, or the use of structural counter-measures such as a modification in the location of seams, elimination of the crowding of seams, reduction in the number of fish plates, etc.

Cracks are induced most frequently in structures and joints where multi-axial internal stresses are evolved. Experience shows that the appearance of cracks during welding under frost conditions is most frequent in the case of closed structural shapes where the evolution of considerable internal stresses is unavoidable.

For the last ten years, the accumulated experience in the construction and exploitation of [storage] tanks points to a considerable number of cases of crack formation due to brittle disintegration of welded seams and the adjacent zones of the basic metal. These disintegrations were taking place during the process of welding and assembling of the structure, or sometime after the welding was completed, or even after a prolonged period of operation of the welded structure.

Below, typical examples of the above are to be found, from data by A. S. Fal'kevich(37) and V. I. Shabalin(38).

The formation of cracks directly in the process of welding and assembling of the storage tanks is comparatively rare, and is most frequently due to the use of the basic metal or electrodes with an excessive content of carbon, sulfur, and phosphorus. However, even when steel and electrodes of normal composition were used, a series of cases of crack formation in the welded seams and in the adjacent zones were registered.

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In the winter of 1944, at one of the construction sites during the welding of the butt-ends in the bottom longitudinal plates of a 4690-cubic meter storage tank, cracks appeared in the butt-welded joints. It must be noted that in the construction of this tank serious technological infractions were committed as follows: the butt-end seams were welded up after the welding of the lap joints connecting the separate bottom plates along their long edges was completed, i.e. under conditions of rigid attachment. In the process of constructing the storage tanks at low temperatures, there were also observed in many cases embrittlement cracks forming in the welded seams and in the basic metal at the moment of peening the bead and punching off the defects with a chisel.

Cases of brittle disintegration of the welded seams and adjacent zones, which occurs in the process of storage tank construction sometime after (1-5 days) the welding of this or that sub-assembly is completed, take place at low temperatures only.

During the winter of 1942-1943, at a surrounding temperature within the range of minus 20-minus 35 degrees Centigrade, a 4690-cubic meter tank under construction, which had in the four lower frame zones two-way rectangular fish plates at the vertical butt-ends which were located 150 millimeters from each other, showed cracks in the basic metal as well as in the welded seams, mostly in directions perpendicular to the seams.

Similarly, storage tanks of the same capacity and type, under construction in 1941-1942, showed ten cracks in their frames.

The welding of all the seams was done with chalk-coated elec-

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trodes, the basic metal used in all above cases was St. 3 steel. The construction of the storage tanks took place under winter conditions at temperatures ranging from minus 14 to minus 37 degrees Centigrade. The cracks were developed after the fish plates were welded on, or after the bead has been peened.

During the mounting of a 4690-cubic meter tank at night, with a surrounding temperature of minus 30 degrees Centigrade, the segmentary circumference of the basic metal around the joint cracked. Simultaneously, cracks were discovered at the four butt-ends of the segments. These cracks were from 100 to 350 millimeters long and 1 millimeter wide. The metal of the segments was 2-3 steel, the electrodes used were Grade E-34. After 4-5 days, at a surrounding temperature ranging from minus 15 to minus 30 degrees Centigrade, 5 more cracks appeared at the segment butt-ends. It was established that during the fabrication and the erection of the segments, tolerances in their butt-ends were excessive (up to 6-8 millimeters).

In the spring of 1943, when welded seams in two storage tanks of the same capacity welded under winter conditions were being tested, cracks were discovered in the basic metal. The construction of these tanks proceeded at temperatures ranging from minus 15 to minus 30 degrees Centigrade.

In 1945, during the fabrication, under winter conditions, of 5 bottoms for storage tanks of the above capacities, several cracks occurred. The tanks were being set up in temperatures ranging from minus 15 to minus 30 degrees Centigrade; the metal used was St. 3 steel, the electrodes were chalk-coated. The cracks were most often located near the butt-joints of the segments, and also in spots where numerous seams crossed.

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At one of the construction sites, where 2-zone 500-cubic-meter-capacity storage tanks were set up under summer conditions, the welded butt-joints of the structural segments and the lower stay angle brackets in the basic metal burst open when, in the winter, the temperature descended to minus 43 degrees Centigrade. These breaks occurred at a time when no work of any kind was being done on the tanks.

Cases are also cited when cracks and breaks in storage tank bottoms and frames occurred a long time after the tanks were in normal operation. All these mishaps were taking place under winter temperatures ranging from minus 20 to minus 40 degrees Centigrade.

In January 1943, at a temperature of minus 30 degrees Centigrade, with a strong wind blowing, the bottom of a 4690-cubic meter gasoline filled storage tank developed a crack to the accompaniment of a loud crackling noise. This tank was constructed under winter conditions, and, after having been water tested, was put into operation in June 1942, thus operating without a stop for a period of 7 months prior to the occurrence of the break.

Another case of crack formation was observed in December 1947 in the frames of several 4690-cubic meter storage tanks. The cracks occurred during the two days when the temperature took a sudden drop from zero to 33-44 degrees Centigrade below zero, and they were localized in the north-western side of the storage tanks which were being hit by the brisk wind.

In all storage tanks which, after passing a water test, were in continuous operation for 5 years, cracks occurred in the most critical stress concentration junction of the lower zone with the

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segmentary circumference and the lower stay angle bracket. These storage tanks were fabricated from low-carbon steel, and chalk-coated electrodes were used in welding.

In 1938, a 4690-cubic meter storage tank filled with fuel oil burst open along its generatrix line, running partly along the seams, but primarily along the basic metal. The damage to the tank occurred at a temperature of minus 27 degrees Centigrade; the character of the break was brittle.

Alongside of the welded seams that were destroyed, several large cracks, located under the structural cover plates, were discovered. The tank was fabricated from St. 3 steel of a normal composition. Impact tests at low temperatures have shown the steel to be cold-brittle. Impact ductility at minus 30 degrees Centigrade was only 0.7 kilograms/square centimeter.

Most of the cracks occur in the butt-welded joints. Cracks are practically never observed in lap joints.

The nuclei for the formation of cracks in welded joints and the adjacent zones of the basic metal are usually defects which have the character of notches (non-fusion, undercut, excessive beading, non-welded craters, dents, punctured lines, etc.), which aggravate the stress composition causing, with the arrival of cold weather, brittle decomposition in the weak spots.

In order to reduce the possibility of brittle disintegration of storage tanks at low temperatures and raise the operating safety factor, the following basic measures are recommended:

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(1) Storage tanks are to be constructed from steel with a carbon content not to exceed 0.2 percent, the content of sulfur and phosphorus not to exceed 0.05 percent each.

(2) The welding of all seams in the bottoms and frames to be done with heavily-coated electrodes, in accordance with GOST 2523-44, which insures high ductility and plasticity of the welded joints.

(3) Strict observance of sequence in the technological process of welding, specifying the maximum possible degree of non-rigid conditions in the welding of components with closed profiles.

(4) Thorough quality control of the welded seams and the inadmissibility of non-fusion, undercuts, local excessive beading, non-filled craters, and other defects which may become nuclei for the evolution of cracks.

(5) The use of butt-welded seams without cover plates.

(6) Unconditional prohibition of peening the bead with the aid of hand-operated or pneumatic chisels at temperatures below minus 10 degrees Centigrade.

Winter welding is not necessarily accompanied by the formation of cracks. Thus, for instance, the steel structural members for the gas generator building of the open-hearth shop at Kuznetskstroy were fabricated under severe winter conditions with no formation of cracks in the welded seams recorded. Moreover, there were cases when welded structural members were dropped, causing disintegration along the basic metal, while welded seams, made under low temperature conditions with the use of chalk-coated electrodes, remain intact(39).

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During the welding process, there may occur in the seams the formation of cracks which cannot be detected on the surface, but will eventually become visible when the welded structure is put into operation.

As pointed out by Academician E. O. Platon, the formation of cracks is conditioned upon the chemical composition of the metal in the seam, which in turn is determined by the chemical composition of the basic metal, the welding electrode metal and coating. The presence in the metal of the welded seam of more than 0.14 percent of carbon, more than 0.25 percent of silicon, more than 0.04 percent of sulfur, and more than 0.05 percent of phosphorus, renders the angle seams in the T-connection liable to cracking(40). It should be noted that the presence of manganese in the steel reduces the tendency to the formation of cracks. The electrode metal may, therefore, contain up to 1 percent manganese.

It follows that, given the proper quality of initial materials, the absence of crack formation in the welding of low carbon steels is practically guaranteed, provided rationally selected high-quality welding cycles are employed. This becomes even more important when the welding is done under conditions of frost.

There is no doubt that the application of advanced automatic welding methods, insuring the homogeneity and high quality of the welded joints, will also eliminate to a considerable degree the formation of cracks.

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Chapter IV

CAUSES FOR THE CHANGE IN THE PROPERTIES OF METALS UNDER THE EFFECT OF LOW TEMPERATURES

One of the basic properties of metals is ductility, i.e. its incapacity to sustain a break without considerable plastic deformation preceding it. This /mechanical/ property is very valuable, since plastic deformation, manifesting itself in a manufactured object during its period of usefulness, indicates an increase in operating stresses above the permissible limits long before disintegration sets in(4).

In crystalline bodies an embrittlement break is different from a ductility break. For instance, in an embrittled state at low temperatures, the monocrystal of iron disintegrates without deformation along the facet of the cube, while in a ductile state, it shows considerable plastic deformation of sliding along the facets, and is disintegrated with the formation of a recess. By subjecting a polycrystalline body to plastic deformation, its mechanical properties can be changed by the creation of a strengthening (cold hardening). In subjecting the toughened metal to brittle disintegration, it can be seen that its strength changes with relation to the degree of plastic deformation imposed upon the metal. This relationship comprises the second physical distinction of brittleness in crystalline bodies.

A strongly pronounced brittleness at some temperatures manifests itself most often in carbon steel.

In examining the changes in the properties of carbon steel with relation to temperature, four clearly delimited zones of brittle-

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ness can be established.

(1) At temperatures below zero Centigrade (cold brittleness;

(2) at 450-500 degrees Centigrade (blue brittleness);

(3) at still higher temperatures, such as 900-1000 degrees Centigrade (red brittleness);

(4) in welding, at the moment of crystallization(42).

The manifestation of the true physical brittleness of iron can be observed in cold brittle breaks, conditioned by the distinct crystallographic characteristics of the disintegration, which very frequently imparts a crystalline flash to the surface of the break.

Cold brittleness is characterized by:

(a) crystalline flash at the surface of the break;

(b) high sensitivity of the critical temperature to deformation notches in the metal;

(c) high sensitivity of the critical temperature to the velocity of load application.

As noted by N. N. Davidenkov(41), cold brittleness is particularly dangerous when impact loads are applied.

It is known that in the area of the ductile state, the resistance of the metal to disintegration, measured by the specific strain of deformation, will increase by several times ten percent, with the transition from static to impact loads. With the increase in velocity, in the absence of cold brittleness, the impact will not only fail to

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aggravate, but will even improve the reaction of the metal to external forces.

Only metals possessing the characteristic of cold brittleness will, under unfavorable conditions, become brittle /throughout/, and the danger of sudden disintegration will be present.

Cold brittleness tests are usually conducted with a whole series of specimens, with the continuous variation of any one parameter. The variable parameter is usually the temperature, but it can also be the form of the /deformation/ notch, the dimensions of the specimen, or the velocity of deformation.

Some metallurgists maintain that with the increase in impact velocity the ductile disintegration of a specimen can be transformed into a brittle disintegration. Still others maintain that the velocity of load application is only a factor of small significance.

Davidenkov is of the opinion that it is most rational to use the temperature as the variable parameter in brittleness tests. He proposes that alongside the conventional computation for strength, a computation for brittleness should be made in order to give the structural designer a more precise idea on the degree of danger presented by the possibility of a brittle disintegration.

Let t_0 be the temperature at which the metal is in service.

Before a brittle break can take place, its temperature must be lowered from t_0 to t_k.

Substituting absolute temperatures T_0 and T_k for the above random temperatures, we can express the temperature ductility reserve

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of a metal by the equation

$$\xi = \frac{T_0 - T_k}{T_0}$$

When $\xi = 0$ ($T_0 = T_k$), the metal has no ductility reserve; when $\xi = 1$ ($T_k = 0$), the possibility of brittle fracture is excluded.

The lowering of the temperature only will not produce a brittle fracture. It is also necessary to increase the working stress σ_0 to the level of the brittle strength σ_r. The ratio $\frac{\sigma_r}{\sigma_0}$ is called force ductility reserve.

In order to determine the ductility reserve of a fabricated object of any form or ~~made~~ make of any material the structural designer must know the critical temperature of the brittle state of the material, which is the temperature at which, under unfavorable conditions, a brittle fracture may occur.

The critical temperature of brittleness is affected by many factors which determine the cellular stresses, the deformation velocity, sensitivity to stress concentration, etc., such as:

(a) geometrical factors (form and dimensions);

(b) mechanical factors (appearance of strain);

(c) impact velocity factor;

(d) technological factors (mechanical and heat treating, surface condition);

(e) chemical factors (the chemical composition of the metal).

Coarse-grain steel has a higher cold brittleness than fine-grain steel. The cold brittleness of steel is also affected by the

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state of the cementite [iron carbide], its form and distribution in the basic ferritic mass. Cold brittleness is decreased with greater dispersion of the cementite particles and with a greater degree of their homogeneous distribution in the basic ferritic mass.

The surface condition, too, even its purely geometrical aspects, considerably affect the brittle strength.

Heat-treating, in particular, affects the cold-brittleness of steel. Aging, in the presence of sulfur and oxygen in the iron, has a considerable effect.

Normalizing improves considerably (as compared to annealing) the properties of steel, decreasing its cold-brittleness. Hardening is still more effective than normalization.

Amelioration (hardening with subsequent tempering) displaces the critical range of brittleness, in some cases 100 degrees Centigrade toward the low temperatures.

Silicon is a rather active promoter of cold brittleness in steel. The presence of nickel is reflected favorably by reducing the impact brittleness in the low temperature range. Many maintain that nickel steels, to the degree in which their nickel content is increased, approximate in their mechanical properties nickel itself, which, as is known, has a higher plasticity in liquid hydrogen (minus 253 degrees Centigrade), than at room temperature. Thus, chromium-nickel steel, containing 6 percent chromium and 24 percent nickel, at the temperature of liquid air showed a 61 percent elongation, and only the temperature of minus 253 degrees Centigrade reduced its elongation to 25 percent.

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With relation to the effect of other special admixtures, it can be pointed out that the properties of alloyed steels depend greatly on heat-treatment.

The sorbitic structure, obtained under normal conditions in low alloy pearlitic steels, contributes to the fact that these steels are less cold brittle than carbon steels.

Many explain crack formation at low temperatures by the cold brittleness of the metal(43). A. P. Tulyakov(44) explains the behavior of metal at low temperatures by the crystallographic lattice in its structure. Metals having a face-centered [crystallographic] lattice retain their impact ductility down to minus 180 degrees Centigrade. Such a face-centered crystallographic lattice is characteristic of most of the non-ferrous metals and of high-alloy austenitic steels. Metals of the face-centered cubic structure do not retain their impact ductility at low temperatures. Such a face-centered cubic structure is characteristic of the pearlitic and ferritic steels.

And yet the explanation of brittleness in metals as due entirely to its atomic structure is not entirely satisfactory, since it is in contradiction to certain facts. For example, certain brasses with a crystallographic structure identical to that of carbon steels, are, nevertheless, non-brittle at very low temperatures.

Academician A. F. Ioffe(45), in his thesis on the strength of crystals, maintains that the disintegration of the metal with the formation of brittle breaks occurs at the moment when the elastic limit attains the magnitude of the true resistance to rupture in tension.

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It is known that a reduction in temperature causes an increase in the elasticity as well as in the strength of metals.

In carbon and low alloy steels, the elastic limit under the above conditions increases more rapidly than its ultimate strength. In non-ferrous metals, the reverse is true. Yet, a low temperature (let us say, minus 180 degrees Centigrade), by itself, cannot cause an increase in the elastic limit up to the magnitude of its ultimate strength (Footnote: That is, not counting individual outer fibers and stress concentration areas where the elastic limit does attain the magnitude of the ultimate strength with disintegration following).

It is obvious that brittleness at low temperatures is induced mainly by stress concentration in certain areas (cracks, scales, fine cracks, hard components, such as carbides, martensite in chromium-nickel steels, etc.) The size as well as shape of the carbide particles affects the stress concentration. In carbon steels, cementite is encountered in larger particles than in alloy steels of the pearlitic class, which causes carbon steels to be more brittle.

This explains the positive effect of hardening on the behavior of steels at low temperatures. As a result of hardening, a more homogeneous structure with fine rounded grains of cementite is obtained and the possibility of stress concentrations is reduced, resulting in the appearance of brittleness only at very low temperatures. Non-ferrous metals, in general, do not have any brittle components where stress concentrations can take place.

E. M. Shevandin[46], in evaluating the effect of velocity of deformation and temperature on the properties of metals while impress-

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ing a punch into the surface of the metal, has shown that, with the impact made at room temperature, the zone of deformation around the imprint is strongly localized (in comparison with the effect of a static load applied), the grains are sharply distorted and elongated along the imprint. With the temperature reduced to minus 196 degrees Centigrade and the application of a static load, the deformation of the grains is comparatively insignificant, although the localization of the deformation is approximately identical with that obtained under the impact test. At the same time, the plastic deformation (impressing the punch) at a low temperature is accompanied by the appearance of a great number of twin crystals.

When, in testing steel, the temperature is reduced to minus 196 degrees Centigrade for static loads, and the rate of load application is brought up to impact velocity, at room temperature the area of plastic deformation is reduced.

It is notable that the magnitude of the area of deformation around the impression made by the punch in the static test, at minus 196 degrees Centigrade, is equal to the one made in the impact test at plus 20 degrees Centigrade. The deduction can be made that the temperature being reduced to minus 196 degrees Centigrade exerts a considerably more intensive effect upon the resistance to deformation and the acceleration of the tendency to brittleness than the conventional impact velocities of 2-5 meters/second at plus 20 degrees Centigrade.

The author maintains further that a reduction in temperature as compared to an increase in impact velocity has a specific effect.

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The effect of low temperatures is manifested by the formation of numerous twin crystals during plastic deformation.

A. A. Bochvar(47) points to the fact that the reduction of temperature to the lowest levels now attainable does not render metals absolutely brittle, i.e. incapable of plastic deformation. It is confirmed by the lastest research that, in the case of most metals, the reduction in temperature causes a comparatively slow reduction in the plasticity of their monocrystals.

A. A. Bochvar assumes that cold brittleness at low temperatures is characteristic of all metals with similar crystallographic lattice (space-centered cube). It is tied in with the deformation characteristics of a given type of crystallographic lattice, and is manifested with particular clarity during impact tests.

In the case of iron and its alloys, cold brittleness manifests itself beginning with zero Centigrade to minus 150 degrees Centigrade, and is expressed by the reduction in impact ductility from 12-25 to 0.5 kilogram/per square centimeter.

The temperature, beginning with which the impact ductility value is decreased, varies with relation to the composition and structure of the steel.

In low carbon steels, devoid of admixtures, brittleness appears at temperatures below zero, and is particularly pronounced at minus 50 and minus 100 degrees Centigrade.

Excessive sulfur, phosphorus, and carbon will cause brittleness in steels at room temperature, and sometimes even at temperatures

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above that.

From the above, the following deductions can be made:

(1) Brittleness at low temperatures is determined mainly by stress concentration in certain areas (cracks, scales, fine cracks, hard components, such as carbides, martensite in chromium-nickel steels, etc.) Stress concentration is affected by the size and shape of the carbide grains. In carbon steels, the cementite occurs in larger grains than in alloy steels of the pearlitic class, therefore, carbon steels are more brittle.

The absence of brittle components in non-ferrous metals is responsible for the absence of stress concentration areas. Therefore, non-ferrous metals retain their ductility at low temperatures.

(2) Low temperatures under conditions of static loads have a greater effect on the resistance to deformation and on the increase in the tendency to embrittlement than impact loads at room temperature.

(3) Brittleness greatly depends on the chemical composition of the steel. A high content of sulfur, phosphorus, and carbon may cause embrittlement at room temperature and even at higher temperatures.

(4) Cold brittleness at low temperatures is manifested with particular clarity in impact tests.

(5) In a state of embrittlement at low temperatures, the monocrystal of iron is ruptured without deformation along the face of the cube, as demonstrated by the occurrence of more numerous cracks

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under frost conditions. In this case the break has straight and even edges, bearing witness to the brittle nature of the break.

(6) Crack formation at low temperatures, in the opinion of many metallurgists, is due to the cold brittleness of metals, manifesting itself in a sharp reduction of its capacity for plastic deformation under conditions of frost.

Cold brittleness is only one of the conditions creating the possibility of disintegration. In itself, the tendency of the metal to become brittle cannot induce disintegration, i.e. the appearance of cracks without the presence of additional factors. For example, in the disintegration of welded seams, an important part is played by Class I internal stresses, the evolution of a state of multi-axial strain during the welding of parts with closed profiles and numerous welded seams, excessive admixtures in the steel, etc.

Chapter V

STUDY OF WELDED JOINTS EFFECTED UNDER LOW SURROUNDING TEMPERATURES

I. AVAILABLE DATA ON THE PROPERTIES OF WELDED SEAMS MADE AT LOW TEMPERATURE

1. Manual Electric Arc Welding

The first studies in the USSR of physical, chemical, and mechanical properties of welded seams, which were effected by electric arc and gas welding under conditions of low surrounding temperatures, were made by Professor E. M. Kuzmak(48). Welding experiments were made at a surrounding temperature of minus 20 degrees Centigrade with

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St. 4 steel sheet sections. The ultimate strength, ductility, angle of bead, and hardness of the welded specimen were determined. In addition, the specific gravity and the chemical composition of the deposited metal, the weld heat imput, the coefficient of beading, the macro and micro structures were determined.

It was established that a surrounding temperature down to minus 20 degrees Centigrade does not cause any changes in the physical and mechanical properties of the welded joints.

V. I. Strokopytov (Tomsk Polytechnical Institute imeni S. M. Kirov)[49] conducted experiments with electric arc welding of structural steel at low temperatures. The steel was 10 millimeter mild rolled sheet of the following composition: C = 0.15 percent; Mn = 0.49 percent; Si = traces; S = 0.024 percent; P = 0.046 percent. Chalk-coated and heavily-coated electrodes were used.

Figure 8 shows the results of mechanical tests of the deposited metal, when the welding was performed with OMM-5 electrodes. The welding was done at surrounding temperatures ranging from plus 10 to minus 40 degrees Centigrade. The welded specimen were tested under normal temperature.

The metallographic investigation did not show the presence of any defects in the deposited metal, when the welding was done at low surrounding temperatures. In all cases the weld deposit was compact, without cracks, slag inclusions, or gas holes. The angle of the bead decreased with lower surrounding temperatures.

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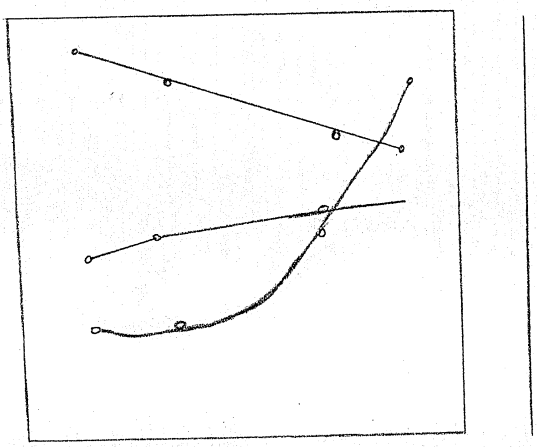

Figure 8. Mechanical properties of the weld metal (basic metal St. 3 steel, electrodes Grade OMM-5) at room temperature as related to the surrounding temperature, at which the welding was done.

Metallographic tests of the welded seam metal of the fusion zone and the metal of the heat affected zone ascertained that the lowering of the temperature to minus 40 degrees Centigrade does not perceptibly affect the structure of the welded seam metal.

The welding of low-carbon steel at low temperatures was also studied by T. M. Slutskaya (Electric Welding Institute, Academy of Sciences, Ukrainian SSR)(50). She determined the ductility of the welded seam metal at normal temperature and at minus 20 degrees Centigrade.

In order to increase the impact ductility of the weld metal at a low temperature, nickel (up to 1.2 percent), ferro-molybdenum and increased quantities of ferro-manganese were incorporated into the coatings of the OMM-5 electrodes. The welding was done on 12-millimeter low carbon steel plates with the use of 5-millimeter electrodes by a 250-ampere current. The testing for impact ductility was done at minus 46 degrees Centigrade.

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The tests established that the yield point increased somewhat, the ultimate strength was somewhat less, and the impact ductility decreased considerably, becoming at minus 30 degrees Centigrade less than 5 kilograms/square centimeter.

In addition to the welding of the above described specimens, test welds were made from low carbon steel (0.18 percent carbon) at temperatures minus 36-minus 38 degrees Centigrade, as follows: a longitudinal butt-weld seam, 0.9 meters long, with 8-millimeter wall thickness; a longitudinal T-weld seam, 0.5 meters long, 10-millimeters thick; a circular-weld seam in a pipe, 110 millimeters in diameter, 14 millimeters in wall thickness; the welding of a connecting pipe, 76 millimeters in diameter, with 6-millimeter walls, to a pipe 110 millimeters long with 14 millimeter walls. A C current and 5-millimeter electrodes were used.

The average impact ductility in the above weld metal was 6.3-6.8 kilograms/square meter, and the angle of the bead was 180 degrees. The testing was done at normal temperature.

Where, in the above tests, the welding was done with quality-coated electrodes, no cracks occurred either in the seam metal or in the metal of the heat affected zone. When chalk-coated electrodes were used, cracks were discovered in the welded seam metal. The author makes a deduction that steel with a carbon content not above 0.20 percent, can be safely welded at temperatures down to minus 30 degrees Centigrade with nickel-containing electrodes. Alloy steels were not within the range of the above described experiments.

I. I. Kokhov[5] welded pipes fabricated from low carbon steel (C = 0.13 percent) with OMM-5 electrodes, with the following results

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of mechanical tests (See Table 24).

Table 24. Welded Seams Made At Different Temperatures -- Results of Tests.

Temperatures in Degrees Centigrade	Ultimate Strength in kg/mm^2	Angle of bead in Degrees	Brinell Hardness No.		
			Welded Seam	Fusion Zone	Heat Affected Zone
+10	43.8	180	147	136	126
- 5	44.6	150	138	114	114
-15	44.9	140	142	138	129
-25	44.7	128	140	129	118
-32	44	116	144	134	118

The above welding was done in the winter at the following temperatures: plus 10, minus 5, minus 15, minus 25, and minus 32 degrees Centigrade.

As can be seen from Table 24, the lowering of the surrounding temperature does not affect the ultimate strength of the welded seam metal. The hardness of the weld metal and the basic metal in the adjacent zone, likewise did not change. The angle of the bead, and consequently the ductility of the welded seam, is reduced with the reduction in the surrounding temperature.

Determination of the strength of welded seams made at low temperatures was conducted also by P. P. Markushev(52) at the "Krasnoye Sormovo" Plant. Butt-welded joints in low carbon steel were tested. The electrodes used were either bare or chalk coated. The surround-

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ing temperatures were plus 15, minus 15, and minus 26 degrees Centigrade.

The results of the mechanical tests are cited in Table 25, from which it can be seen the surrounding temperature, at which the welding was done, had little effect on the mechanical properties of the seam metal.

Table 25. Welded Seams in Low Carbon Steel Made at Different Temperatures -- Results of Tests.

Temperature at Which Welding Was Done in Degrees Centigrade	Type of Electrodes	Ultimate Strength of kg/mm^2	Angle of Bead in Degrees
+15	Bare	37	65
+15	Chalk-coated	40	75
- 5	Bare	36.7	85
- 5	Chalk-coated	40	85
-26	Bare	40.4	75
-26	Chalk-coated	39.0	75

E. I. Belenya[30] conducted experiments relating to the strength of butt-welded joints in St. 3 Steel, made at surrounding temperatures ranging from minus 10 to minus 40 degrees Centigrade. Various types of electrode coating and various current strengths were being tested in welding under surrounding frost conditions. Electrodes used were as follows: chalk-coated, SK-1-coated, and OMM-5-coated. The current was 240-250 amperes Results are given in Table 26.

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Table 26. Strength of Butt-Welded Joints Made at Various Surrounding Temperatures.

Electrode Coating	Ultimate Strength in kg/mm^2 at Temperature				
	-20 C	-10 C	-20 C	-30 C	-40 C
Chalk	32	31.7	34.8	33.5	34.4
SK-1	--	32.9	31.5	37.0	30.4
OMM-5	34	37.7	35.5	36.8	36.8

The optimum welding cycle under frost conditions (from minus 20 to minus 30 degrees Centigrade) was also being determined in these experiments, with results as follows:

Current Amperage	100	160	200	250
Ultimate Strength in kg/mm^2	28.5	29.4	30.0	32.2

This confirms the feasibility, in welding under frost conditions, of using stronger electric current, which is being done by our Stakhanovite welders.

V. D. Taran, in experimenting with the weldability of steels with various carbon content, on the basis of determining the hardness of the welded seam and the adjacent zones, discovered, that medium carbon steels (up to 0.34 percent carbon) can be safely welded at surrounding temperatures down to minus 30 degrees Centigrade without any technological complications.

K. M. Olifirenko and V. P. Vologdin[32] experimented with shipbuilding steel of the following chemical composition: C = 0.31 percent; Mn = 0.6 percent; Si = 0.35 percent; S = 0.05 percent; P = 0.05 percent.

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During the tests, the basic metal (the plates) were thermostatically cooled to minus 20 and minus 60 degrees Centigrade, while the temperature of the surrounding air remained normal. It was established that the depth of the welding penetration is reduced when the surrounding temperatures are low. The experiments by Olifirenko and Vologdin, and also by Markushev, established the fact that the width of the heat affected zone is reduced when welding is done at low temperatures.

The intensity of the initial heating of the plate being welded under various surrounding temperatures is closely tied in with the width of the heat affected zone. When the temperature of the surrounding air and the basic metal is reduced, the width of the heat affected zone is also reduced. This points to the non-homogeneity in the initial heating of the seam zone, and to a higher cooling rate, which may, in some cases, lead to great thermal strains. Thus, the reduction in the area of the heat affected zone, in welding under conditions of surrounding frost, is undoubtedly tied in with the strength of the welded seams, and, with relation to other factors, it may be either beneficial or harmful.

I. I. Kokhov(51), E. I. Belenya(30), and P. P. Markushev(52), in experimenting with the welding of low carbon steels under frost conditions, have established the absence of structural differences in the weld metal deposited under various temperatures.

K. M. Olifirenko and V. P. Vologdin(32) made a detailed investigation of the temperature distribution in welding, and of the variations in the micro-structure of the metal which are tied in with it. They observed the perceptible effect of the initial temperature of the

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metal upon the width of extension of the zone of the over-heated metal and the zone of the normalized metal, and also the variations of the metal structure in these zones. In plates with an initial temperature of plus 125 degrees, the width of the over-heated zone was at its maximum (1.3 millimeters), the metal has a coarse-grained and sharply pronounced Widmanstätten structural pattern. In plates with an initial temperature of plus 20 degrees, the over-heated zone was reduced to 0.8 millimeters in width, with the Widmanstätten structural pattern still sufficiently perceptible. With further lowering of the temperature, the width of the over-heated zone was further reduced, and the Widmanstätten structural pattern gradually disappeared. In plates with an initial temperature of minus 60 degrees the zone of the over-heated metal, as well as the Widmanstätten structural pattern were completely imperceptible.

This is the effect of a short heating period and an accelerated cooling rate of the metal. With the lowering of the initial temperature of the plates, the width of the heat affected zone is reduced, but together with this the temperature differential in the adjacent areas and the cooling rate of the metal are increased. The acceleration of the cooling rate, in the opinion of the authors, has an unfavorable effect on the zone of the so-called "normal metal". The cooling velocities are so considerable (up to 250 degrees per second, at normal temperature of the surrounding air, and up to 270 degrees per second, at minus 60 degrees), that instead of normalization there is hardening, yet a somewhat unusual hardening, with an accelerated cooling rate at the beginning, and a retarded cooling rate subsequently.

Changes in the micro-structure of the heat affected zone were

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noticed during the lowering of the initial temperature of the metal, but these changes were not considered to be negative.

2. Automatic Welding Under a Layer of Flux

B. I. Medovar and A. E. Asnis (Electric Welding Institute, Academy of Sciences, Ukrainian SSR)(53) experimented with the automatic welding of metal structures from low carbon steel at low surrounding temperatures.

Two cases were investigated: automatic welding under normal temperature conditions, with subsequent testing at a low temperature; and welding under frost conditions, with subsequent testing at a low temperature.

The welding was done with low carbon 5-millimeter electrodes, 900-950 ampere current, at a welding speed of 18 meters per hour under AN-3 flux.

The results of testing these specimens for impact ductility are cited in Table 27.

[See next page for Table 27]

The following deductions can be made from the above cited Table:

(a) The metal of the seam, welded at a low temperature, and subjected to subsequent further chilling, has shown, at all test temperatures, a somewhat lowered impact ductility (on the average, by 20-25 percent), as compared with the metal of the seam that was welded under normal temperature conditions and then chilled.

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TABLE 27

IMPACT DUCTILITY TESTS OF SPECIMENS AUTOMATIC - WELDED UNDER A LAYER OF FLUX

Conditions under which welding was done	Impact ductility in kilograms per square centimeter at temperatures					
	+15 degrees Centigrade	0 degrees Centigrade	-20 degrees Centigrade	-30 degrees Centigrade	-50 degrees Centigrade	-65 degrees Centigrade
Welding at normal temperature with subsequent chilling of specimens	10.4	9.9	8.6	7.1	5.6	2.95
Welding of chilled specimens with subsequent chilling	8.0	--	6.5	5.2	1.8	2.2

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The impact ductility of the metal in the seam that was welded under frost conditions, when tested at minus 20 degrees is in excess of 4 kilograms/per square centimeter. At normal temperature, the impact ductility is in accordance with GOST (8 kilograms/square centimeter).

As seen from this test data, automatic welding under frost conditions with the use of low carbon electrodes, and under a layer of AN-3 flux, is feasible.

The testing of specimens for cold brittleness was done by tapping the specimens with a hammer until cracks appeared. Results are shown in Table 28.

[See next page for Table 28]

The hardness and the structure of the metal in the seam and the heat affected zone were the same in both cases. Some technological peculiarities in the welding, under flux, of chilled specimens were noted.

For instance, the lower the temperature of the specimen being welded, the more defects appear in the welded seam. This is obviously due to the fact that there is a more intensive heat elimination from the walls of the welding bath, causing the latter to solidify more rapidly, which circumstance renders the exit of the gases from the bulk of the liquid metal more difficult. In welding under frost, the welding penetration is somewhat smaller in depth than in welding under normal temperature. Best results are obtained with vitreous flux.

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TABLE 28

BRITTLENESS TESTS OF AUTOMATIC-WELDED SPECIMENS

Temperature under which Welding was done	Steel	Welding Cycle: Strength of Current in Amperes	Welding Cycle: Voltage	Welding Cycle: Welding speed in meters per second	Temperature of crack formation
Normal	High-damping capacity (C= 0.19 percent)	1000 - 1100	35	18	At minus 5 degrees, from a light tap with 0.4 kilogram hammer.
40 degrees Centigrade	The same	1000 - 1100	40	18	At minus 15 degrees, from a blow with 10 - 12 kilogram hammer.
Normal	Low-damping capacity (c= 0.14 percent	1000 - 1050	32 - 34	17	At minus 50 degrees, from a blow with 10 - 12 kilogram hammer.
40 degrees Centigrade	The same	1000- 1050	34	15	At minus 48 degrees, from a blow with 10 - 12 kilogram hammer.

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Taking into consideration the harder labor conditions involved in the operation and control of chilled welding equipment, in working with cold metal, also the unfavorable effect of low temperatures on welding equipment, the Electric Welding Institute maintains that open-air electric welding at frost temperatures is not to be recommended except in emergencies.

The above data establishes that:

(1) the ultimate strength and hardness of welded seams made at low temperatures is further increased with reduction in temperature;

(2) the impact ductility of seams welded at low temperatures is decreased with the reduction in test temperatures;

(3) low and medium carbon steels (up to 0.32-0.34 percent carbon) do not show any perceptible change in the micro-structure of the seams when the welding is done under lower surrounding temperatures.

II. EXPERIMENTS CONDUCTED IN THE WELDING LABORATORY OF THE MVTU (MOSCOW TECHNICAL COLLEGE) IMENI BAUMAN

The author conducted an investigation into the mechanical properties of welded joints effected at low temperatures. The following Grades of steel were involved.

(1) Low alloy low carbon SKhL-2 (2 melts) structural steel of a chemical composition as indicated in Table 29.

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Table 29. Composition of SKhL-2 Steel

Number of Melt	Components in Percent								
	C	Mn	Si	Cr	Ni	Cu	Mo	S	P
112535	0.2	0.74	0.41	0.59	0.54	0.4	0.08	0.020	0.034
17127	0.14	0.61	0.45	0.67	0.42	0.35	--	0.025	0.037

SKhL-2 steel had the following mechanical properties (Table 30):

Table 30. Mechanical properties of SKhL-2 Steel

No. of Melt	kg/mm^2	kg/mm^2	percent	a_k kg/cm^2
112535	39—42	60—64	19—21	13.5—19.9
17127	35	53	23	13.6

(2) Grade 50 steel, of the following chemical composition: C = 0.5 percent; Mn = 0.96 percent; Si = 0.23 percent; S = 0.018 percent; P = 0.017 percent; Ni = 0.13 percent.

(3) St. 3 steel of the following composition: C = 0.11 percent; Mn = 0.44 percent; Si = 0.16 percent; S = 0.012 percent; P = 0.014 percent.

The welding of these steels was done with electrodes of these two grades: OMM-5 and T_sL-5. Welded seams effected at minus 40, minus 30, minus 20, minus 10, zero, and plus 18 degrees Centigrade were being tested. The test temperatures were minus 40 degrees and room temperature. Simultaneously with the determination of the mechanical properties of the welded seams, effected at low temperatures, the tendency of the steels to crack formation was studied.

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The thermal condition of the plates in the process of welding, and the deformation of the plates were also studied.

The welding was done in a special refrigeration chamber in the Moscow Refrigeration Research Institute. The refrigerated chamber had an area of 5.73 square meters, a height of 2.1 meters, a volume of 12 cubic meters. The chamber was refrigerated by wall and ceiling ammonia coils, with a total cooling surface of 29 square meters. The indicated cooling surfaces permitted the introduction into the chamber of cold to the amounts of 2900 kilo-calories per hour, with the loss of cold through the surface amounting to 224 kilo-calories per hour.

The rated temperature of the chamber is minus 57 degrees, but it is possible to bring it down to minus 63 degrees.

The required temperatures (minus 40, minus 30, minus 20, minus 10) were created in the chamber 3-4 hours ahead of the test.

The plates to be tested were brought into the chamber 4-5 hours ahead of the test so that their temperature may be considered the same as the temperature of the chamber. In the chamber was the object to be welded, the welder to perform the necessary work, and an observer to write down the results. The considerable capacity of the refrigerating plant permitted the maintenance of a strictly constant temperature throughout the experiment.

To determine the effect of low temperatures on the mechanical characteristics of the welded seam (ultimate strength, angle of bend, impact ductility), 65 pairs of plates from SKhL-2, St. 3, and Grade 50 steel were butt-welded at temperatures ranging from plus 18 to minus 40 degrees Centigrade.

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The welding was done with AC current delivered from an STE-32 welding transformer. The current strength and the arc voltage were fixed with the aid of the usual laboratory devices. The burning time of the arc was recorded by a stopwatch, the temperature in the chamber by an alcohol thermometer.

From the indicated 65 pairs of plates, 1200 specimens were prepared for testing ultimate tensile strength, impact ductility and angle of bend. Out of these 1200 specimens, a part was tested at normal temperature, a part at minus 40 degrees. Figure 9 shows the specimen cut-out diagram for these tests.

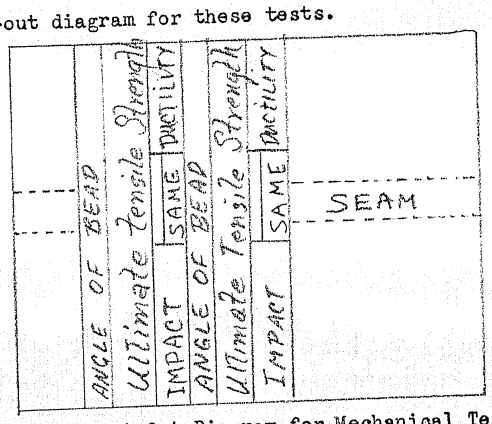

Figure 9. Specimen Cut-Out Diagram for Mechanical Tests.

In preparing the specimens for impact ductility tests (prior to milling the notches), they were pickled in a 5 percent solution of nitric acid for a more accurate delineation of the zone of fusion.

The shape and size of the test specimens were in accordance with $\frac{OST}{NKT}$ $\frac{7687}{663}$. A sketch of a specimen for tensile strength testing is given in Figure 10.

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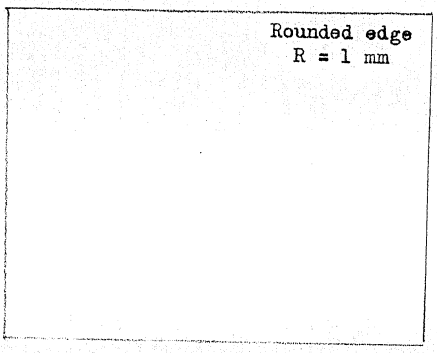

Figure 10. Sketch of Specimen for Tensile Strength Test.

The plates for the mechanical tests were of the following dimensions:

Grade of Steel	Dimensions
SKhL-2	250 x 100 x 10 millimeters
50	350 x 120 x 12 millimeters
St. 3	250 x 100 x 8 ÷ 12 millimeters

Out of the general number, 15 welded plates were X-ray examined prior to cutting. The radiograms showed that low temperatures during the welding operation have no effect on the homogeneity of the welded seams.

For the testing of the specimens for impact ductility, angle of bend, and ultimate strength, special devices were constructed so as to allow of the determination of the above mechanical characteristics in the welded seams at low temperatures.

1. Methods for the Mechanical Testing of Specimens at Low Temperatures.

For the testing of specimens at low temperatures, special refrigeration devices were designed and fabricated as described below.

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Samples were tested for impact ductility, ultimate strength, and angle of bead at minus 40 degrees. Before testing, the samples were dipped into an ethyl alcohol and dry ice (solid carbon dioxide). This mixture was of the temperature required by the test, or a few degrees below. After the assigned time lag, insuring the complete chilling of the samples, they were removed from the mixture, and tested.

The temperature cycle was regulated by additions of ethyl alcohol and dry ice into the refrigeration box (Figure 11), as required.

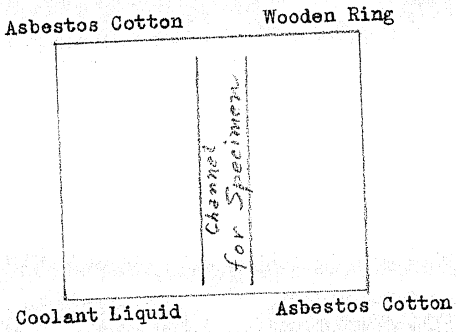

Figure 12. Cooling Device.

Elongation and bending tests were performed in a universal testing machine. The specimens for elongation tests (Figure 10) had 10 millimeter holes drilled through their ends for clamping into the testing machine.

The refrigeration device for testing samples at minus 40 degrees is shown in Figure 12.

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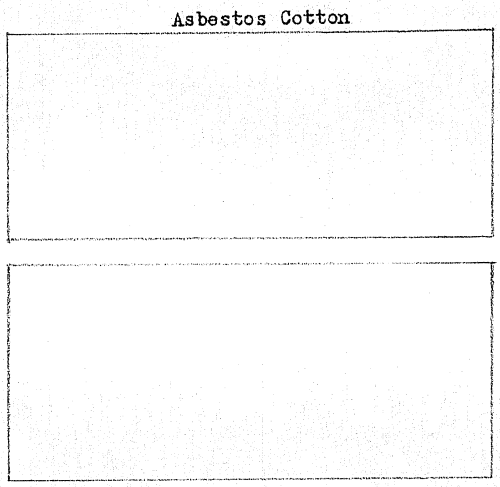

Figure 11. Refrigeration Box

This device made it possible to refrigerate the specimens, and to maintain the required temperature practically continuously throughout the test. Figure 13 shows the refrigeration device clamped into the universal testing machine. The device has a double wall, which is filled in with heat-insulating material. Inside is a tube into which the specimen is inserted. The space between this tube and the double wall is filled with dry ice. For reading the temperature of the specimen, a thermometer is placed in a ring which is communicating with the tube containing the specimen. The specimen is held in position by rods which in turn are clamped into the testing machine.

Bending tests at low temperatures were also performed in the universal tension-testing machine. The specimens were chilled for 40 minutes in a refrigeration box in a mixture of dry ice and ethyl alcohol with a temperature of minus 65 degrees. The supports, on which the specimen rested, were chilled by dry ice packed between

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them. The temperature of the specimen at the time of the test was registered by a thermocouple, the junction of which was placed into a hollow which was drilled into the lateral side of the specimen at a distance of 20 millimeters from welded seam axis.

The testing of the samples for the angle of bend, as well as for tensile strength, was done at minus 40 degrees. The loading of the specimen was discontinued with the appearance of the first crack on the side of the specimen opposite the penetrator application spot.

Impact ductility tests were conducted in a pendulum-type impact testing machine with an ultimate impact energy of 15 kilograms. The chilling of the specimen in accordance with Menagé (with a notch in the center of the seam) was effected in a refrigeration box down to minus 42 degrees. The samples were placed into the refrigeration box in batches of 20 to 30 pieces then grabbed up with cold tongs, rapidly carried to the machine, and tested.

By overchilling the specimen by 2 degrees as compared to the test required temperature, the warming effect sustained during the test is compensated for. In all the tests conducted, the specimens were never in the air longer than 7 to 8 seconds.

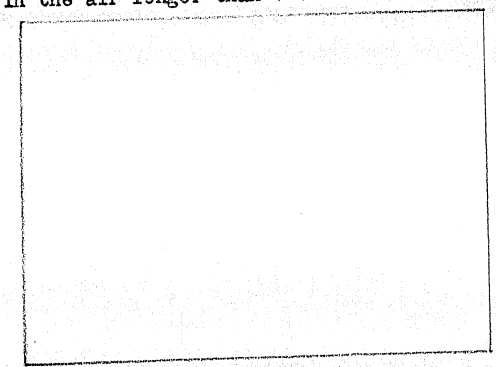

Figure 13. Installation of Refrigerating Device in the Testing Machine (1 - rod; 2 - chilling device; 3 - thermometer).

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It may be assumed that when the specimen is taken out of the coolant liquid a gas film is formed on its surface. This film tends for some time to retard the loss of cold by the specimen, rendering its temperature continuous for the first few seconds. This, however, requires additional research.

2. Crack Formation Tests.

As pointed out before, steels at low temperatures become more brittle. Therefore, welding at these temperatures is dangerous, due to the tendency of the metal to develop cracks in the welded seam and in the heat affected zone.

To check this premise, tests were conducted with 16 millimeter SKhL-2 steel plates welded in a rigid attachment (Figure 14). The formation of cracks was determined in the control seam, the last one to be set up. The dimensions of the control seam were 4 x 4 and 4 x 5 millimeters.

The purpose of the test was to determine the effect of temperature on crack formation in the welded seam and in the heat affected zone. The welding of the control seam was effected at minus 40, minus 30, minus 20, minus 10, zero, and room temperature, respectively, by AC current, with the use of 4 to 5 millimeter OMM-5 and T_sL-5 coated electrodes.

Eight pairs of 16 millimeter SKhL-2 steel plates were welded in rigid attachment and tested for crack formation. Results are given in Table 31.

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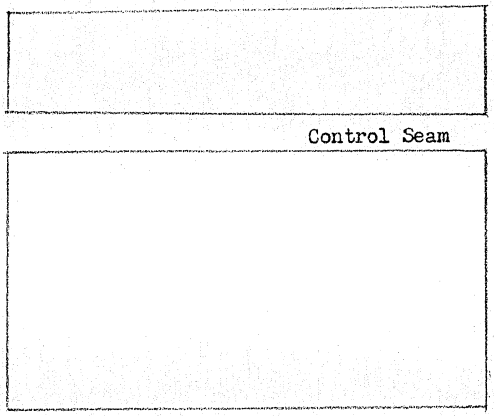

Figure 14. Device for Testing the Crack Formation in the Welding of SKhL-2 Steel in Rigid Attachment.

/See next page for Table 31/

The control seam and the heat affected zone in the basic metal were examined for macrostructure.

For welded T-joints of small cross sections (such as 5 x 5 millimeters), in plates of considerable thickness and at the temperature of minus 40 degrees, a large number of hot cracks was discovered (Table 31).

Templets, cut out of 16 millimeter SKhL-2 steel plates, which were welded in rigid attachment with OMM-5 electrodes, showed a 1 millimeter tensile crack in the weld metal (See Figure 15). In addition, there are ruptures with the depth of the depth of the initial crack up to 1.15 millimeters. The templets were pickled in a 2 percent nitric acid solution in ethyl alcohol. A considerable part of the cracks formed during this test were discovered by the superficial use of a magnifying glass.

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TABLE 31

RESULTS OF TESTS FOR CRACK FORMATION IN 5 X 5 MILLIMETER CONTROL SEAMS OF 16-MILLIMETER SKhL-2 STEEL PLATES WELDED IN RIGID ATTACHMENT

Temperature under which welded (1)	Grade of Electrode (2)	Diameter of electrode in millimeters (3)	Type and strength of current (in amperes) (4)	Control number of test (5)	REMARKS (6)
- 40 degrees Centigrade	TsL - 5	5	AC - 230	1	Seam compact, good; Longitudinal 3-millimeter crack in crater area
-40 degrees Centigrade	OMM-5	4	AC - 200	2	At 30 millimeters from start, transverse crack becomes longitudinal for distance of 12 millimeters; at 98 millimeters from start, a 12 millimeter longitudinal crack; from this point 5 millimeters of compact seam, then a 30 millimeter longitudinal seam to end.
-30 degrees Centigrade	OMM-5	4	AC - 200	4	Seam compact for a distance of 84 millimeters then porous for 30 millimeters with longitudinal checks in the recesses; 3 millimeters of longitudinal crack; 3 millimeters of compact seam; longitudinal crack to the end.
-30 degrees Centigrade	TsL-5	5	Ac - 230	3	Seam compact, good; intermittent longitudinal checks in crater area.

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(1)	(2)	(3)	(4)	(5)	(6)
-20 degrees Centigrade	TsL-5	5	AC -230	5	Good compact seam; longitudinal checks in crater area.
-10 degrees Centigrade	TsL-5	5	AC - 220	6	64 millimeter of good compact seam; 30 millimeters of blister without cracks; 45 millimeter of good compact seam; 14 millimeter longitudinal crack to end of crater.
0 degrees Centigrade	TsL-5	5	AC - 220	7	Good compact seam, with dotted porosity in crater.
18.4 degrees Centigrade	TsL-5	5	AC - 230	8	Good compact seam all along; small longitudinal checks in crater.

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A microsection and photo prepared from a rigid attachment welding specimen of 16 millimeter SKhL-2 steel plate with the use of OMM-5 electrodes at minus 30 degrees, showed the presence of a tensile fracture in the deposited metal of the welding seam, originating in a crack at the depth of 2 millimeters (See Figure 16).

The method of pickling and the degree of enlargement were analogous to same in the preceding specimen.

In addition, the examination of the welded seam in this specimen welded under rigid attachment showed a considerable number of cracks discernible without magnification.

Welding seams made with TsL-5 electrodes at the same temperatures (minus 40 and minus 30 degrees) had no cracks in the weld metal.

These experiments confirmed the deductions of G. A. Nikolayev and N. N. Prokhorov(4) relating to the effect of the surrounding temperature on crack formation in welding. Crack formation in welding is more frequent at sub-zero surrounding temperatures than at normal temperatures.

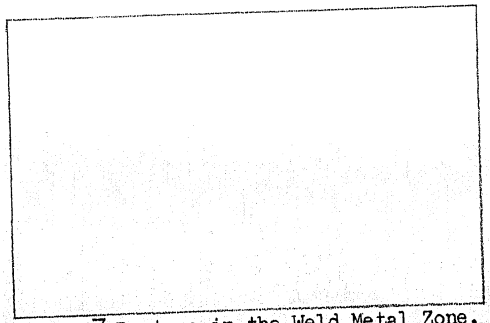

Figure 15. /Microphoto/ Rupture in the Weld Metal Zone, SKhL-2 Steel, Temperature Minus 40 Degrees Centigrade.

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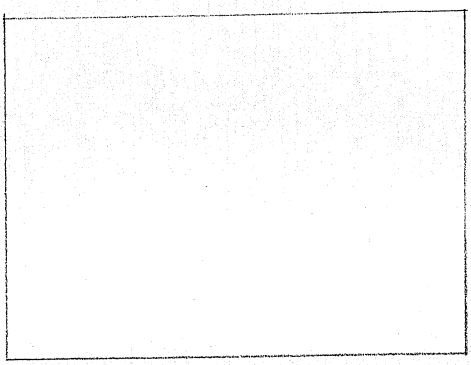

Figure 16. /Microphoto/ Rupture in the Weld Metal Zone, SKhL-2 Steel, Temperature Minus 30 Degrees.

In the above depicted experiments for crack formation in the welding of SKhL-2 steel under rigid attachment, crack formation increases with the lowering of the surrounding temperature.

Obviously, in addition to the surrounding temperature, the technological process employed in the welding operation also has its effect upon the formation of cracks. Experiments by G. A. Nikolayev and N. N. Prokhorov show that formation of cracks in self-hardening steels is decreased with the preliminary preheating of the joints prior to welding.

Thus, crack formation experiments established that in welding SKhL-2 steel under low surrounding temperatures:

(1) mainly hot cracks develop, which can be deducted from the oxide film on the fracture, indicating a high temperature of formation.

(2) The reduction in the surrounding temperature accelerates the formation of hot cracks which is confirmed by the presence of cracks in the control seams of samples, welded in rigid attachment

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at the surrounding temperatures of zero, minus 10, minus 20, minus 30, and minus 40 degrees.

(3) The use of OMM-5 electrodes in welding under frost conditions results in crack formation, while the use of TsL-5 electrodes on the same steels under analogous conditions does not result in crack formation.

3. Heat Distribution in the Plate at Time of Welding under Normal and under Low Surrounding Temperatures.

In order to study the thermal condition of the metal being welded, experiments relating to the heat distribution in plates at the time of the welding operation, under minus 40 and zero degrees of the surrounding temperature, were conducted. Grade 50 steel plates, 350 x 120 x 12 millimeters thick, were used. The operation consisted of beading 165 to 170 millimeter fillets onto the rib of the plate.

The welding cycles are depicted below in the maximum temperature graphs. Prior to welding, chromel-alumel thermocouples were clamped onto the plates at points where temperature readings were to be taken, as per diagram in Figure 17.

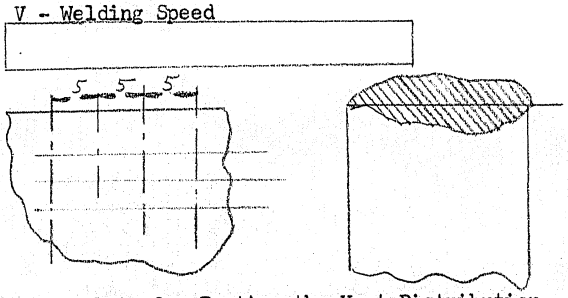

Figure 17. Plate for Testing the Heat Distribution.

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The nearest thermocouple was located at a distance of 2 to 4 millimeters from the fillet to be welded. The thermocouple terminals were calked into lunes which were recessed to a depth of 0.5 to 1 millimeter, since, if the thermocouple junction becomes welded directly to the surface of the metal plate, the temperature reading will be lower due to the elimination of heat along the thermocouple wires.

The reading and the registration of temperature at the indicated points in the plate during the welding operation were done with the aid of a thermograph designed by the Section for Electric Welding and Electrothermics, Academy of Sciences, USSR (panel RP-45) which reads the temperature at six points simultaneously. This device is also equipped with a time recorder and, simultaneously with the temperature readings, it records the amperage and the voltage of the current.

Two tests at the surrounding temperature of minus 40 degrees were made under minimum welding cycles with 4 millimeter OMM-5 electrodes with I = 190 ÷ 200 a, U = 24 ÷ 24 v.

The subsequent tests were made at minus 40 degrees under maximum welding cycles: two with the use of 5 millimeter TsL-5 electrodes with I = 260 ÷ 270 a, U = 33 ÷ 34 v, and one test with 5 millimeter OMM-5 electrodes with I = 300 a, U = 27 v.

The tests at zero temperature were also made under minimum and maximum welding current strength.

For plotting the curves of heat distribution in the plate being welded, the following equation by N. N. Rikalin(54) was utilized:

$$T_{(y_0,t)} = \frac{2q}{v\delta\sqrt{4\pi\lambda c\gamma t}} e^{-bt - \frac{y_0^2}{4at}}$$

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where $q = 0.24\eta_i IU$, the effective capacity of the arc in calories per second;

v is the speed of travel of the arc in centimeters per second;

δ is the thickness of the plate in centimeters;

λ is the coefficient of heat conductivity of the metal in calories/centimeters x seconds degrees Centigrade;

c is the thermal capacity in calories/grams degrees Centigrade;

γ is the specific gravity in grams/centimeters^3;

$a = \frac{\lambda}{c\gamma}$ is the coefficient of temperature conductivity in centimeters^2/seconds;

$b = \frac{2\alpha}{c\gamma\delta}$ is the coefficient of temperature elimination 1/seconds;

α is the coefficient of temperature elimination from the finite air surfaces in calories/centimeters^2 seconds degrees Centigrade;

t is time in seconds;

y_0 is the distance of the given point from welded seam;

T is the temperature of the given point in the plate in degrees Centigrade, read with relation to the initial temperature T_0, which equals the temperature of the surrounding air.

The results of the tests for the study of the heat distribution in the plate being welded are presented graphically in Figures 18-23 in the form of maximum temperature curves.

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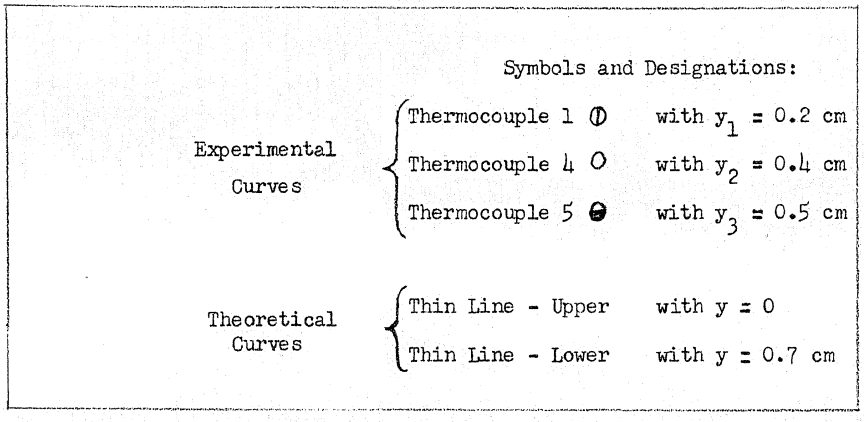

Figure 18. Thermal Distributions Curves

Test No 1 (T = -40 degrees Centigrade; I = 200 a; U = 26 v; v_{cv} = 0.47 cm/sec; δ = 1.2 cm; b = 30 x 10^{-4}; η_i = 0.6.

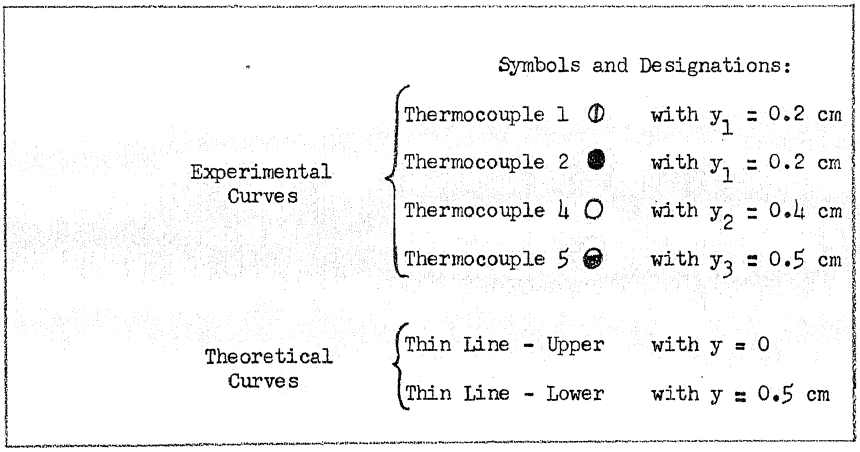

Figure 19. Thermal Distribution Curves

Test No 1. T = +2 degrees Centigrade; I = 170 a; U = 24 v; v_{cv} = 0.4 cm/sec; δ = 1.2 cm; b = 30 x 10^{-4}; η_i = 0.8.

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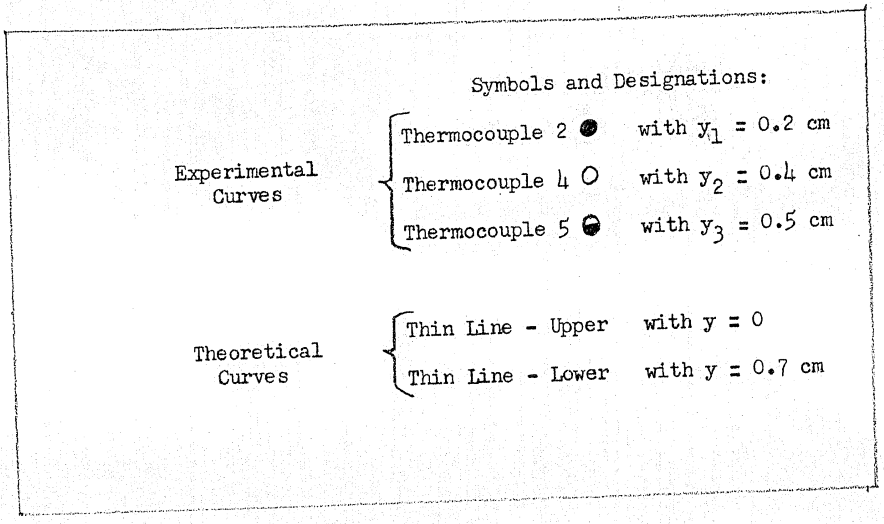

Figure 20. Thermal Distribution Curves

Test No 2. T = -40 degrees Centigrade; I = 200 a; U = 26 v; v_{cv} = 0.4 cm/sec; δ = 1.2 centimeters; b = 29 x 10^{-4}; $\eta\dot{\varepsilon}$ = 0.6.

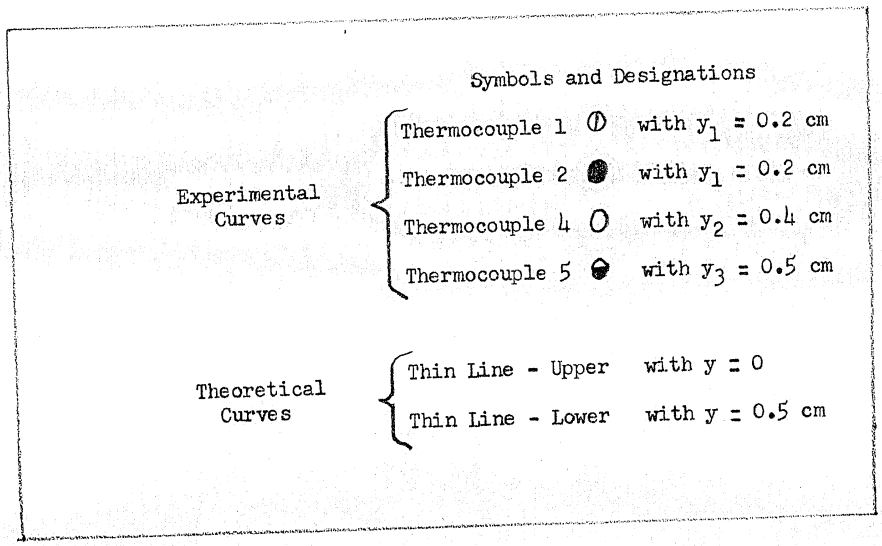

Figure 21. Thermal Distribution Curves

Test No 2. T = +2 degrees Centigrade; I = 160 a; U = 24 v; v_{cv} = 0.4 cm/sec; δ = 1.2 centimeters; b = 18 x 10^{-4}; $\eta\dot{\varepsilon}$ = 0.8.

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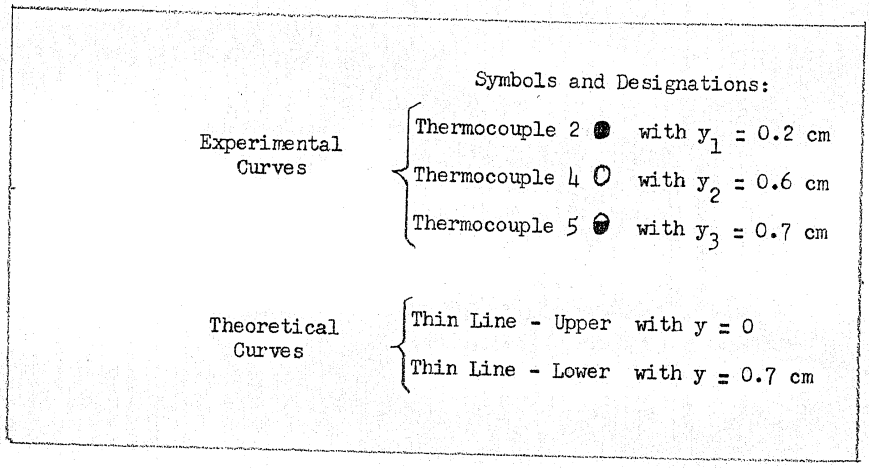

Figure 22. Thermal Distribution Curves

Test No 3. T = -40 degrees Centigrade; I = 270 a; U = 32 v; v_{cv} = 0.6 cm/sec; δ = 1.2 centimeters; b = 30 x 10^{-4}; ηi = 0.6.

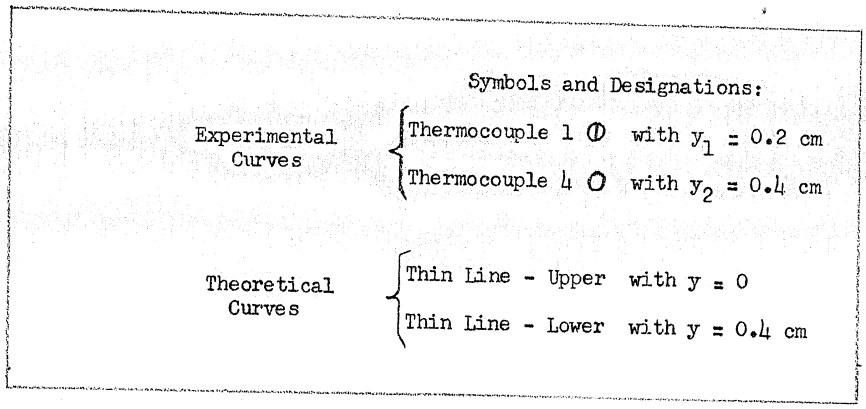

Figure 23. Thermal Distribution Curves

Test No 3. T = +2 degrees Centigrade; I = 260 a; U = 23 v; v_{cv} = 0.4 cm/sec; δ = 1.2 cm; b = 30 x 10^{-4}; ηi = 0.8.

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Experiments with the measuring of temperatures during the welding operation show that the maximum temperatures at points equidistant from the welded seam are lower when welding is done at a minus 40 degrees surrounding temperature than when the same is done at zero surrounding temperature. For example, at a distance of 0.2 centimeters from the welded seam the maximum temperature of a Grade 50 steel plate 350 x 120 x 12 millimeters thick, with the welding done at zero degrees, was plus 1000 degrees Centigrade. At the same distance from the welded seam (all other conditions being equal) the maximum temperature, with the welding done at minus 40 degrees surrounding temperature, is only plus 875 degrees Centigrade. At a distance of 0.7 centimeters from the seam, the maximum temperature in a plate of the same Grade 50 steel when welded at zero surrounding temperature, was plus 650 degrees Centigrade, while, when welded at minus 40 degrees surrounding temperature, /all other conditions being equal/ it was only plus 450 degrees Centigrade.

The maximum temperatures in the cross-sections, the nearest to the welded seam, are the greatest. With distance from the welded seam, the maximum temperatures diminish.

The maximum temperature curves, which were arrived at experimentally, are, in their characteristics, sufficiently close to the theoretical curves.

4. The Effect of the Surrounding Temperature on the Plastic Deformation of Plates in Beading Fillets onto Edges.

In superimposing welded seams, particularly in beading onto plate edges, the metal in the heat affected zone along the seam is subject to compression stresses when heated and to tension stresses when cooled. Since the metal in the zone of the seam is subject to

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alternate high magnitude stresses of compression tension, it must have good plasticity characteristics. At temperatures of 300 to 400 degrees Centigrade, at which the plastic properties of many steels are diminished (blue brittleness), cracks may develop in the welded joint.

To determine deformations during the beading of fillets onto edges, tests were made with SKhL-2 steel plates which, in order to eliminate the internal stresses resulting from the rolling and the gas /acetylene torch?/ cutting of the plates, were subject to high tempering at 650 to 750 degrees Centigrade. The plates were 300x100x8 millimeters thick. On the face of the plates 9 lunes were punched out on each side at a distance of 10 millimeters from each other. The disposition of the lunes on the faces of the plates is shown in sketch (Figure 24).

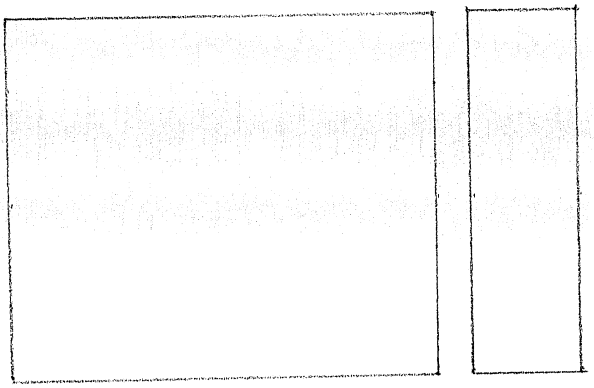

Figure 24. Plate for Measuring Deformations (Beading of Fillet Onto Edge).

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The beading of the fillet onto the edge was done by hand operation with TsL-5 and OMM-5 electrodes, AC current delivered from an STE-32 transformer at 200-220 amperes, and at surrounding temperatures ranging from plus 20 to minus 40 degrees Centigrade. The longitudinal deformations running parallel to the fillet, which developed as a result of the beading, were measured by the method of Professor G. A. Nikolayev(55).

The longitudinal deformations were measured by a deformometer which was made out of a rigid rod with cleats at its ends and an indicator head. The measuring of the lengths was done prior to, and after, the beading. The absolute values of these deformations are cited in Table 32, while in Table 33 the same deformation values are computed in percent.

Figures 25 and 26 are graphs showing the deformations in relation to the welding temperatures in beading fillets onto the edge with OMM-5 and TsL-5 electrodes under various surrounding temperatures.

Figure 27 is a graph showing the deformation with relation to the welding temperature (electrodes OMM-5 and TsL-5 used) at point 1.

This data shows that:

(a) deformation of the elements of the plates does not, to any great degree, depend on the surrounding temperature.

(b) the electrode coating practically has no effect on the deformation of the plate.

In beading with OMM-5 electrodes, the deformation of the plate at a distance of 10 millimeters from the beaded edge at minus 10 degrees surrounding temperature is equal to 0.275 millimeters. At a

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distance of 40 millimeters it is equal to 0.106 millimeters. At a distance of 90 millimeters it is equal to 0.052 millimeters. At a surrounding temperature of minus 40 degrees, the deformation of the plate 10 millimeters from the beaded edge is 0.233 millimeters; at 40 millimeters it is 0.105 millimeters; at 90 millimeters from the beaded edge it is 0.068 millimeters.

In beading with TsL-5 electrodes, the deformation of the plate under plus 18.4 degrees surrounding temperature at 10 millimeters from the beaded edge was 0.300 millimeters; at a distance of 40 millimeters it was 0.112 millimeters; at a distance of 90 millimeters it was 0.071 millimeters. Under a surrounding temperature of minus 40 degrees with the same TsL-5 electrodes used the deformation at 10 millimeters from the beaded edge was 0.340 millimeters; at 40 millimeters it was 0.162 millimeters; at 90 millimeters it was 0.062 millimeters.

The figures cited prove that changes in the surrounding temperature do not essentially affect the magnitude and distribution of residual deformations.

It may be assumed that in the welding of other types of joints the effect of the surrounding temperature on the magnitude of residual deformations is of little importance. This deduction holds true for electric arc-welded SKhL-2 steel objects which are 8 millimeters and above in thickness. It is probable that in the case of lesser thicknesses the magnitude of residual deformations in welding under surrounding frost will increase. Bearing in mind that most of the structural elements are fabricated from steel which is 8 millimeters and above in thickness, the deduction about deformations not being affected by surrounding temperatures may be extended to a large range of industrial processes.

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TABLE 32

MAGNITUDE OF DEFORMATION IN MILLIMETERS

Material	Kind and Strength of material in amperes	Grade and diameter of electrode	Surrounding temperatures under which welded	Magnitude of deformation at a distance from beaded edge (in millimeters)								
				10	20	30	40	50	60	70	80	90
SKhL-2 Steel Plate 300 x 100 x 8 millimeters	AC I = 220	OMM - 5 5 millimeters	-10	0.275	0.211	0.142	0.106	0.075	0.008	0.005	0.028	0.052
			-20	0.236	0.188	0.148	0.112	0.064	0.034	0.000	0.033	0.069
			-30	0.257	0.214	0.137	0.108	0.074	0.037	0.005	0.054	0.066
			-40	0.233	0.198	0.153	0.105	0.062	0.028	0.002	0.030	0.068
	AC I = 200	TsL - 5 5 millimeters	+18.4	0.300	0.240	0.180	0.112	0.080	0.004	0.007	0.028	0.071
			-10	0.254	0.178	0.135	0.092	0.055	0.024	0.012	0.048	0.083
			-30	0.260	0.186	0.130	0.094	0.065	0.040	0.008	0.006	0.055
			-40	0.340	0.280	0.220	0.162	0.097	0.055	0.012	0.029	0.062

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TABLE 33

MAGNITUDE OF DEFORMATION IN PERCENT

Material	Kind and strength of current in amperes	Grade and diameter of electrodes	Surrounding temperature (when welded)	Magnitude of deformation at a distance from beaded edge - in percent								
				10	20	30	40	50	60	70	80	90
SKhL - 2 steel plate 300 x 100 x 8 millimeters	AC I = 220	OMM - 5 5 millimeters	-10	0.0917	0.0703	0.0474	0.0353	0.0250	0.0027	0.0017	0.0093	0.0173
			-20	0.0787	0.0627	0.0493	0.0373	0.0213	0.0113	0.0000	0.0110	0.0230
			-30	0.0856	0.0713	0.0457	0.0360	0.0246	0.0123	0.0017	0.0180	0.0220
			-40	0.0777	0.0660	0.0510	0.0350	0.0207	0.0093	0.0007	0.0100	0.0227
	AC I = 200	TsL - 5 5 millimeters	18.4	0.1000	0.0800	0.0600	0.0373	0.0267	0.0013	0.0023	0.0093	0.0237
			-10	0.0847	0.0593	0.0450	0.0307	0.0183	0.0080	0.0040	0.0160	0.0277
			-30	0.0866	0.0620	0.0433	0.0313	0.0217	0.0133	0.0027	0.0020	0.0150
			-40	0.1133	0.0933	0.0733	0.0540	0.0323	0.0183	0.0040	0.0097	0.0207

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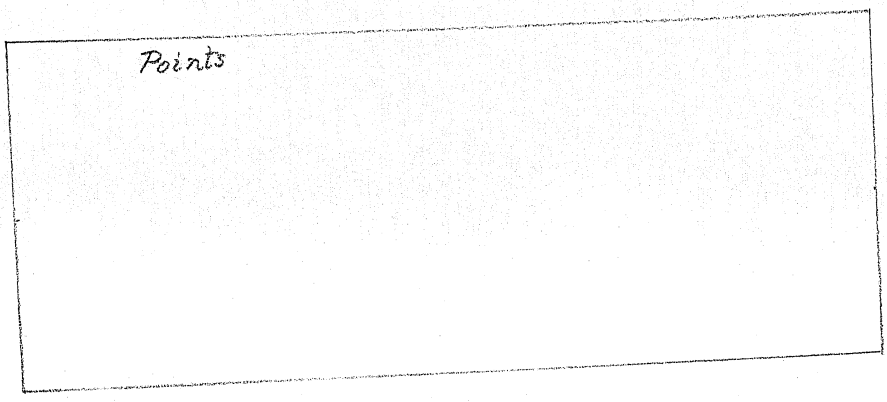

Figure 25. Deformation - Surrounding Temperature Curve, Electric Arc Welding, 5-millimeter TsL-5 Electrodes, I = 200 amperes, U = 33 volts.

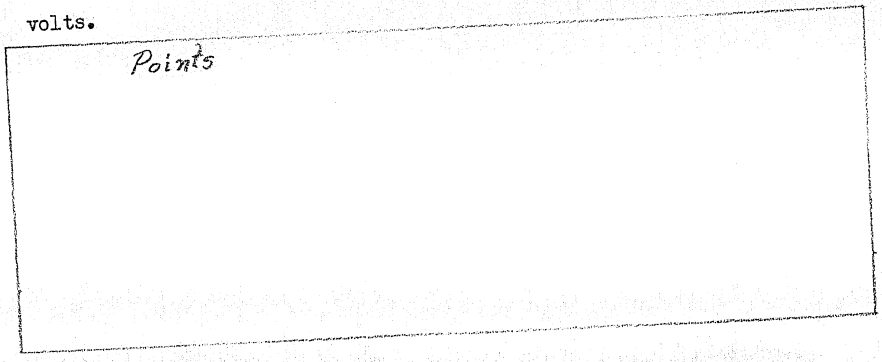

Figure 26. Deformation - Surrounding Temperature Curve, Electric Arc Welding, 5-millimeter OMM-5 Electrodes, I = 220 amperes, U = 25 volts.

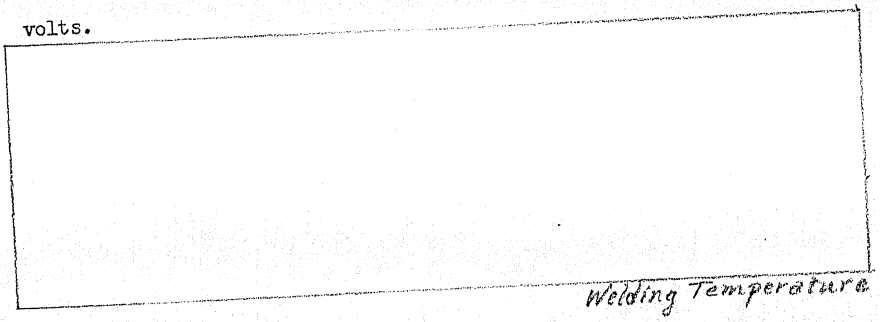

Figure 27. Deformation - Surrounding Temperature Ratio at Point 1 in Welding Cycles as follows: (a) 5-millimeters OMM-5 electrodes; I = 220 amperes; U = 25 volts, (b) 5-millimeter TsL-5 Electrodes; I = 200 amperes; U = 33 volts.

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5. Results of Mechanical Tests on Welded Joints Effected Under Low Surrounding Temperatures.

In conformity with the accepted methods of investigation for the determination of the effect of surrounding temperatures upon the mechanical properties of welded joints, tests were conducted with butt-welded specimens as shown in Figure 28. The angle of taper of the edges was 35 degrees; trucation was about 2 millimeters.

Before welding the plates were set in such a way that there was a clearance of 1.5 to 2 millimeters, after which they were tack welded. The superposition of the welded seam was effected in two passes. After placing the first layer, the plates were cooled for 3 to 4 hours to their initial temperature and the second layer was placed.

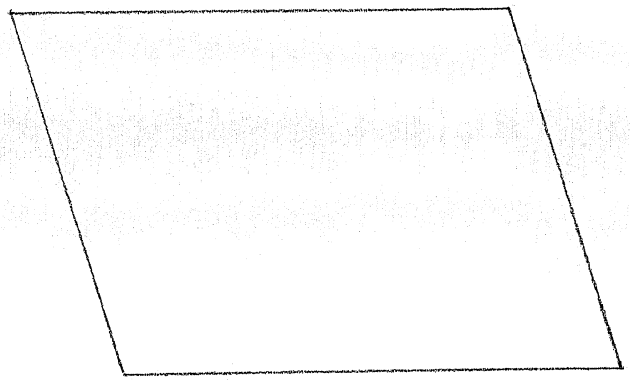

Figure 28. Plates for Butt Welding

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(a) The Effect of Low Surrounding Temperatures on the Impact Ductility of Welded Seams.

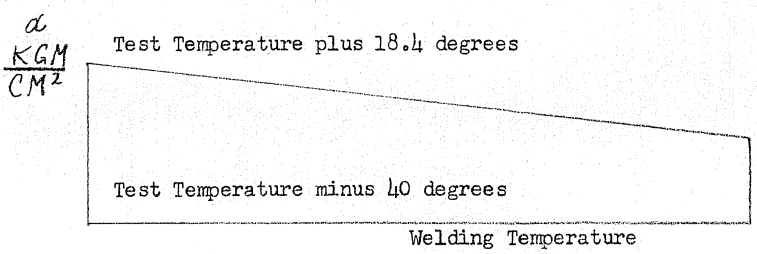

Figure 29. SKhL-2 Steel; Melt No 63202; 5 Millimeter TsL-5 Electrodes; 100 x 300 x 10 Millimeter Plates; I = 240 Amperes; 2 Layer Seam.

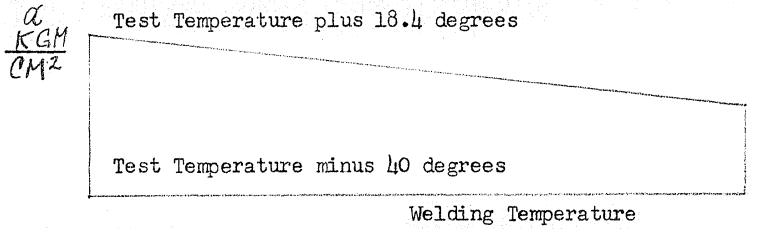

Figure 30. SKhL-2 Steel; Melt No 112535; 5 Millimeter OMM-5 Electrodes; 100 x 300 x 10 Millimeter Plates; I = 240 Amperes; 2 layer seam.

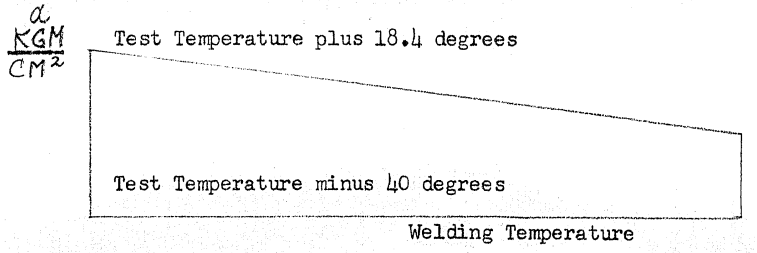

Figure 31. St. 3 Steel; 100 x 300 x 10 Millimeter Plate; 5 Millimeter TsL-5 Electrodes; I = 240 amperes; 2 Layer Seam.

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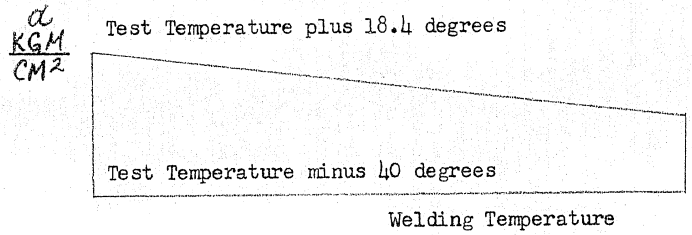

Figure 32. St. 5 Steel; 120 x 360 x 12 Millimeter Plate; 5 Millimeter OMM-5 Electrodes; I = 240 amperes; 2 Layer Seam.

Speciments for determination of impact ductility were made from the plates. Testing was done at minus 40 degrees and at plus 18 degrees Centigrade. The graphs in Figures 29 to 32 depict the results of the tests, showing the functional relationship between impact ductility and the surrounding temperature under which the welding was done.

Tests at plus 18 degrees Centigrade. Analyzing the results obtained, the following can be noted.

(1) with the reduction in the surrounding welding temperature the impact ductility in the welded seams of 3 investigated grades of steel is reduced.

(2) The sharpest reduction in impact ductility occurs in SKhL-2 steels (from 7 to 37 percent). When OMM-5 electrodes were used, impact ductility was somewhat higher than with the use of TsL-5 electrodes.

(3) St. 3 steel showed a lower degree of reduction in impact ductility (from 5 to 22 percent). Welding with OMM-5 electrodes gave better results.

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(4) In Grade 50 steel, impact ductility was reduced by approximately 10 to 15 percent. Results were the same when either OMM-5 or TsL-t electrodes were used.

Tests at minus 40 degrees Centigrade. The following results were obtained.

(1) The general trend of the impact ductility dropping with the reduction in the surrounding welding temperature remains.

(2) The impact ductility value in welded seams from SKhL-2 steel welded with TsL-5 electrodes is reduced 3 to 4 times. In seams welded under normal surrounding temperature, it is 3 to 4 kilograms per square centimeter, while in seams welded under minus 40 degrees, it is 1 to 2.5 kilograms per square centimeter.

In welding the same SKhL-2 steel with OMM-5 electrodes, the values for impact ductilities are reduced 12 times or more. In seams welded under normal temperature it is 1 kilogram per square centimeter, while in seams welded at minus 40 degrees, it is 0.5 to 0.7 kilogram per square centimeter.

(3) In welding St. 3 steel with OMM-5 electrodes, the impact ductility values are reduced approximately 7 times. Seams welded under normal temperature have an impact ductility value of 1.5 kilograms per square centimeter, while seams welded at minus 40 degrees have an impact ductility value of 0.5 kilogram per square centimeter.

In welding St. 3 steel with TsL-5 electrodes, the impact ductility values decrease by only less than half as compared to the values of same in seams welded under normal surrounding temperature in which they are 4.6 kilograms per square centimeter. It is true that in

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seams welded under minus 40 degrees surrounding temperature, the impact ductility values dropped to 0.5 kilogram per square centimeter.

This circumstance confirms the feasibility of using TsL-5 electrodes for welding under low surrounding temperatures.

(4) In welding Grade 50 steel with OMM-5 electrodes, the impact ductility values are reduced 3 to 4 times; they attain the value of 1.8 kilograms per square centimeter in seams welded under normal temperature, while in seams welded at minus 40 degrees, they are 1.0 kilogram per square centimeter.

Considering the relatively low impact ductility values at normal temperatures for this grade of steel, it becomes obvious that it shouldn't be used at low surrounding temperatures.

(b) The Effect of Low Surrounding Welding Temperature on the Ultimate Strength Values in Welded Seams.

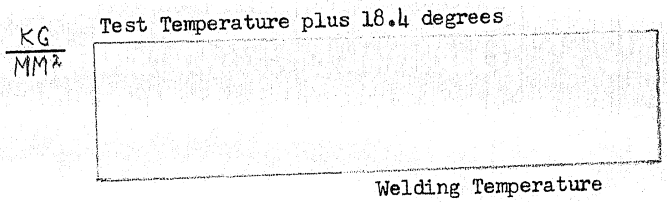

Figure 33. SKhL-2 steel; No of Melt 112535; 5 Millimeter TsL-5 Electrodes; 100 x 300 x 10 Millimeter Plate; I = 240 amperes; 2 Layer Seam.

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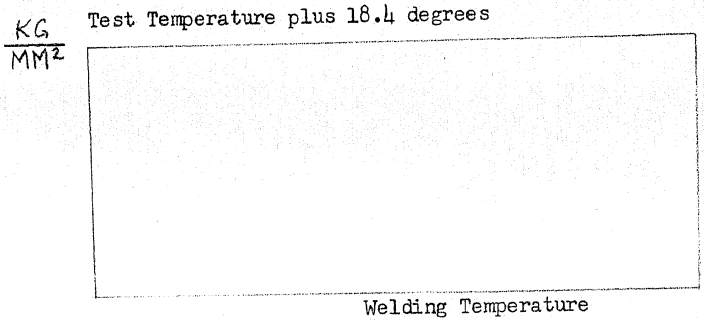

Figure 34. St. 3 Steel; 100 x 300 x 10 Millimeter Plate; 5 Millimeter OMM-5 Electrodes; I = 240 amperes; 2 Layer Seam.

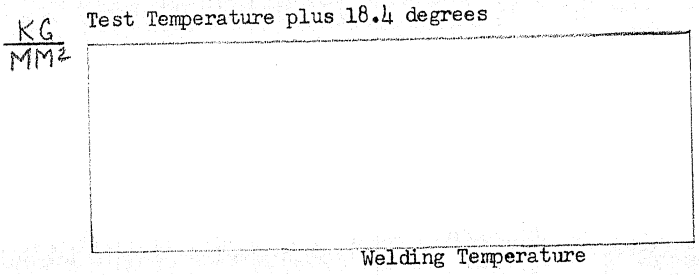

Figure 35. St. 5 Steel; 120 x 350 x 12 Millimeter Plate; 5 Millimeter TsL-5 Electrodes; I = 240 amperes; 2 Layer Seam.

The result of tensile strength tests on welded joints effected at various temperatures are shown graphically in Figures 33 to 35. The tensile tests for the determination of ultimate strength were conducted at plus 18.4 degrees and at minus 40 degrees. The results were as follows.

(1) The ultimate strength of welded joints in SKhL-2, St. 3, and Grade 50 steels, has a tendency to become higher with lower surrounding welding temperatures.

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(2) In SKhL-2 steel, the ultimate strength of welded seams is increased by 3 to 10 percent when welding is done under minus 40 degrees surrounding temperature, as compared with welding done under plus 18 degrees surrounding temperature.

(3) In St. 3 steel, the ultimate strength of welded seams remains unchanged and is not affected by changes in the surrounding welding temperature.

(4) Grade 50 steel shows a more perceptible increase in ultimate strength (from 9 to 17 percent) when welding is done under minus 40 degrees surrounding temperature than when it is done at plus 18 degrees.

As indicated above, the value of ultimate strength at minus 40 degrees was determined. At this temperature, 48 specimens were tested and the results are cited in Table 34.

/See next page for Table 34/

Upon analyzing the Table, the following deductions can be made.

(1) Ultimate strength, as shown by test conducted at minus 40 degrees, rises somewhat by comparison with values obtained in testing at plus 18 degrees.

(2) Welded seams made with TsL-5 Electrodes have somewhat higher ultimate strength values than those made with OMM-5 Electrodes. This was confirmed by tests with specimens from all three grades of steel (SKhL-2, St. 3, and Grade 50).

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TABLE 34

DETERMINATION, AT -40 DEGREES CENTIGRADE, OF ULTIMATE STRENGTH OF WELDED SEAMS EFFECTED BY 2-LAYER WELDING WITH 240-AMPERE CURRENT AND 5-MILLIMETER ELECTRODES

Grade of Steel	Number of Melt	Thickness of Plate in Millimeters	Surrounding Temperature in degrees Centigrade	Grade of Electrodes	Number of Specimens	Ultimate strength in Kilograms per square millimeter		
						Minimum	Maximum	Mean
St. 5	--	12.0	-20	OMM - 5	2	62.5	63.0	62.7
				TsL - 5	2	61.5	66.5	64.0
			-30	OMM - 5	6	64.5	70.0	67.5
				TsL - 5	2	71.5	73.5	72.5
St. 3	--	12.0	-20	OMM- 5	2	57.0	58.0	57.5
				TsL - 5	2	56.0	58.0	57.5
			-30	OMM - 5	4	49.5	52.3	51.0
		8.0	-30	OMM - 5	4	45.0	48.0	46.5
SKhL-2	63202	10.0	-20	OMM - 5	4	58.0	63.5	60.8
				TsL - 5	1	--	--	66.0
			-30	OMM - 5	5	56.0	62.0	59.0
				TsL - 5	1	--	--	64.8
SKhL-2	112535	10.0	-20	OMM - 5	6	54.5	64.0	60.0
				TsL - 5	2	63.0	66.3	64.5
			-30	OMM - 5	4	57.0	59.5	58.5
				TsL - 5	1	--	--	65.0

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(c) Effect of Low Surrounding Welding Temperature on the Angle of Bead in Welded Seams.

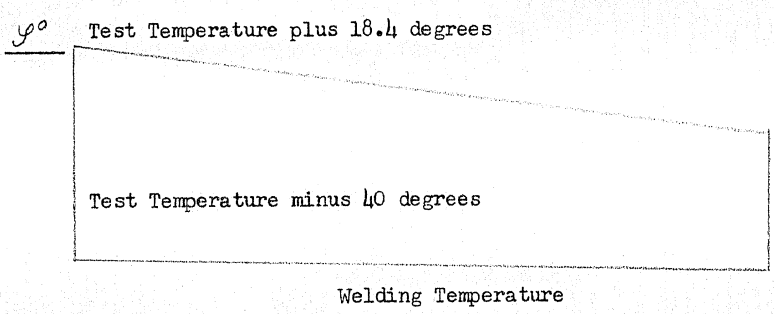

Figure 36. SKhL-2 Steel; No of Melt 112535; 5 Millimeter TsL-5 Electrodes; 100 x 300 x 10 Millimeter Plate; I = 240 amperes; 2 Layer Seam.

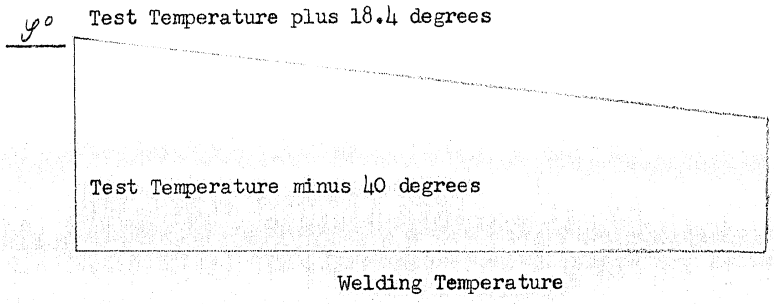

Figure 37. SKhL-2 Steel; Melt No 112535; 5 Millimeter OMM-5 Electrodes; 100 x 300 x 10 Millimeter Plate; I = 240 amperes; 2 Layer Seam.

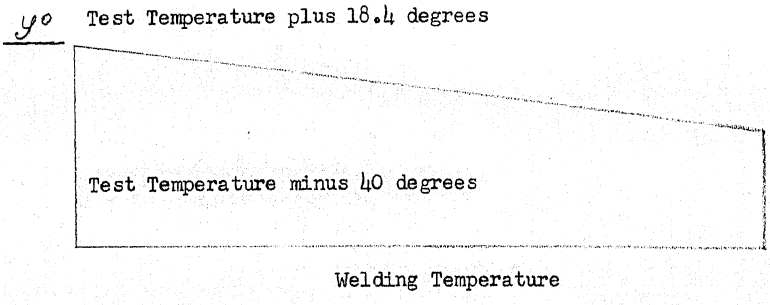

Figure 38. St. 3 Steel; 100 x 300 x 10 Millimeter Plate; 5 Millimeter OMM-5 Electrodes; I = 240 amperes; 2 Layer Seam.

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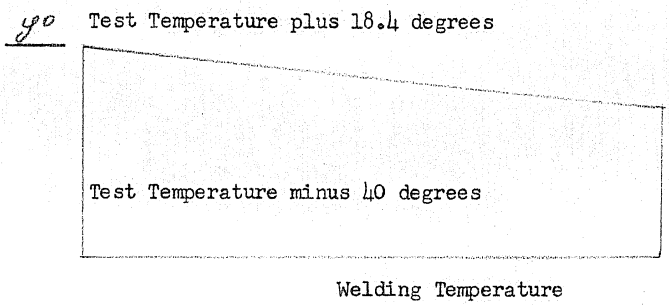

Figure 39. St. 5 Steel; 120 x 350 x 12 Millimeter Plate; 5 Millimeter OMM-5 Electrodes; I = 240 amperes; 2 Layer Seam.

The determination of the angle of bead was made at normal temperature and at minus 40 degrees. Figures 36 to 39 show the results of these tests.

Analyzing the above graphs, the following deductions can be made.

(1) With the reduction in the surrounding welding temperature, the angle of bead diminish somewhat. For example, when SKhL-2 steel was welded with TsL-5 Electrodes under a surrounding temperature of plus 18 degrees, the angles of bead were equal to 120 to 140 degrees, while under a surrounding welding temperature of minus 40 degrees they were from 75 to 116 degrees.

(2) With the lowering of the test temperature, the angles of bead diminished considerably. At a test temperature of plus 18 degrees, in SKhL-2 steel, they were 75 to 90 degrees, while at the test temperature of minus 40 degrees they were equal to 34 to 60 degrees.

(3) In SKhL-2 steel welded specimens that were welded under a surrounding temperature of minus 40 degrees, testing at normal temper-

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atures showed angles of bead of 75 to 116 degrees. This indicates the presence of fully adequate plasticity characteristics in the welded joints of SKhL-2 steel under low temperatures.

(4) Welded specimens of St. 3 steel, tested at normal temperatures, showed even greater angles of bead. Specimens tested at minus 40 degrees showed worse results than analogous specimens from SKhL-2 steel.

(5) Welded specimens from Grade 50 steel showed relatively small values for the angle of bead. At normal test temperatures they were 40 to 75 degrees; at the test temperature of minus 40 degrees, they were equal to 15 to 45 degrees.

(6) Specimens welded with TsL-5 electrodes in most of the cases gave better results, with relation to the values of the angle of bead, than those welded with OMM-5 electrodes.

6. The Effect of Low Surrounding Welding Temperatures on the Hardness of the Seam and the Heat Affected Zone.

The hardness determination was made by using the method of MVTU (Moscow Technical College). In order to determine the effect of low temperatures upon the hardness of the metal in the welded seam and the heat affected zone, 46 tests were made at various temperatures with SKhL-2, St. 3, and Grade 50 steels. TsL-5 and OMM-5 electrodes were used.

55 x 250 Millimeter plates, oxygen cut from SKhL-2 steel, were annealed at plus 850 degrees Centigrade, and soaked for 30 to 40 minutes to eliminate the effect of sub-hardening.

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Grade 50 steel plates, for purposes of hardness tests, were cut to size 55 x 250 millimeters in a milling machine. After the plates were gas-cut, they were planed at their lateral surfaces. Prior to welding, these plates, three in a row, were laid out snugly against each other, and transversely clamped with bolts (as shown in Figure 40.)

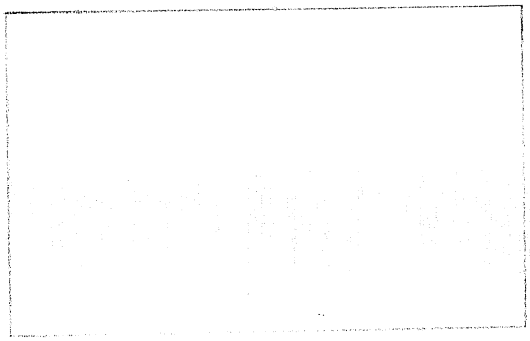

Figure 40. Diagram of Pattern for Hardness Test Specimens.

Then, under various surrounding temperatures, fillets were beaded on. After welding, 10 x 55 millimeter (Figure 40) specimens were cut out from the center of each plate for the purpose of preparing microsections and to determine the hardness in the metal of the welded seam and the heat affected zone. Hardness of the pickled specimens is determined in the cross-section perpendicular to the direction of the seam at the points indicated diagrammatically in Figure 41.

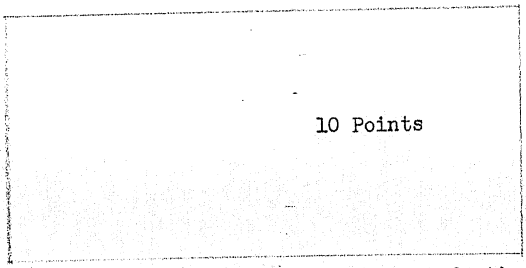

Figure 41. Hardness Measuring Diagram Along Cross-Section Perpendicular to Welded Seam.

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The graphs in Figures 42 to 46 depict the plotted values of hardness in relation to the surrounding temperature of beading fillets onto specimens from SKhL-2, 50, and St. 3 steels.

The Grade 50 steel specimen, welded with OMM-5 electrodes, under a surrounding temperature of minus 23 degrees, hardness was tested at 39 points (spaced 1 millimeter apart), at a distance of one third of the plate thickness from the upper edge, as shown in Figures 41 and 42.

The maximum hardness occurs at points located in the heat affected zone, at a distance of 1 to 3 millimeters from the fusion zone.

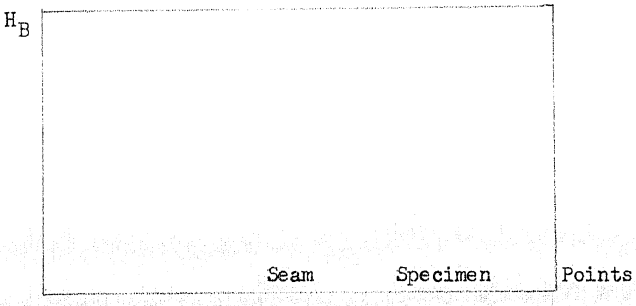

Figure 42. Hardness Curve with Relation to Surrounding Welding Temperature: Grade 50 Steel; OMM-5 Electrodes; Surrounding Temperature Minus 23 Degrees Centigrade.

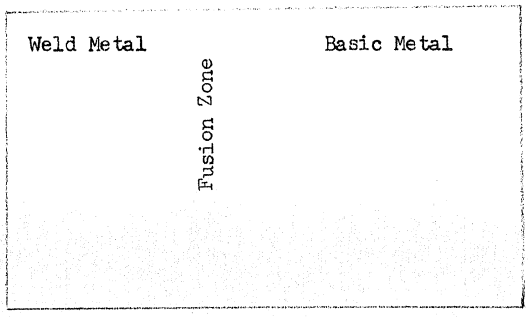

Figure 43. Hardness Curves with Relation to Surrounding Welding Temperature: SKhL-2 Steel; Melt No 63202; 5 Millimeter OMM-5 Electrodes; I = 240 amperes.

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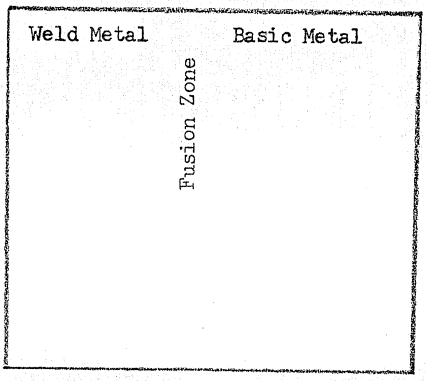

Figure 44. Hardness Curve with Relation to Surrounding Welding Temperature: SKhL-2 Steel; Melt No 112535; 5 Millimeter OMM-5 Electrodes; I = 240 amperes.

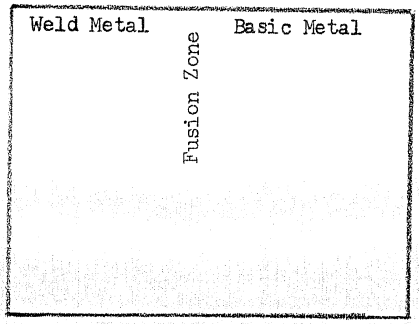

Figure 45. Hardness Curve with Relation to Surrounding Welding Temperature: Grade 50 Steel; 5 Millimeter OMM-5 Electrodes; I = 240 amperes.

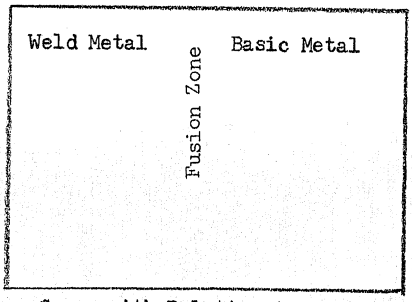

Figure 46. Hardness Curve with Relation to Surrounding Welding Temperature: St. 3 Steel; 5 Millimeter OMM-5 Electrodes; I = 240 amperes.

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The following deductions can be made from the hardness tests:

(1) Reduction in the surrounding welding temperature induces an increase in the sub-hardening of the heat affected zone.

(2) Maximum hardness in butt-welded seams in SKhL-2 and Grade 50 steels occurs at points located at a distance of 1 to 2 millimeters (more frequently at a point 1 millimeter distant from the fusion zone.

(3) In St. 3 steel welded specimens, sub-hardening did not occur even when the welding was done under minus 40 degrees surrounding temperature.

(4) In SKhL-2 steel, sub-hardening occurred at the above indicated points of the heat affected zone with relation to the surrounding temperature of beading the fillets; hardness increased by 220-240 Rockwell units, with the hardness of the basic metal being 150 units.

(5) A particularly pronounced hardening occurred in the heat affected zone of a Grade 50 steel specimen when the beading of the fillet was done at a surrounding temperature of minus 40 degrees. At a point 1 millimeter distant from the fusion zone, hardness was equal to 300 Rockwell units, with the hardness of the basic metal being equal to 150 to 160 units.

7. Results of Metallographic tests.

In welding under low surrounding temperatures, there takes place an accelerated cooling of the welded seam and the heat affected zone, due to a strong elimination of heat into the surrounding atmosphere by the metal being welded.

The accelerated rate of cooling induces corresponding changes

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into the microstructure of the metal.

Specimens for microanalysis were cut out from the welded joints of the three grades of steel under investigation. Two layer seams were used. Control welding seams that were welded under rigid attachment were also microanalyzed. The effect of welding under low surrounding temperatures on microstructural formations was being determined.

The metallographic investigation was conducted after pickling the microtemplets in a 2 percent solution of nitric acid in ethyl alcohol, and under a magnification of X 500. The description of the microstructures obtained in the microanalysis of welded specimens of SKhL-2, St. 3, and Grade 50 steels, which were welded under various surrounding temperatures, are given in Tables 35 through 38 directly below.

Table 35. Welded Microsections from SKhL-2 Steel, TsL-5 Electrodes Used.

Surrounding Welding Temperature	Area From Which Specimen is Taken	Microstructure
40° C		
Microphoto	Weld Metal	Cast coarse-grained dendritic structure
Microphoto	Beginning of Zone	Coarse grain ferrite plus pearlite, generally martensitic

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(1)	(2)	(3)
Microphoto	End of Fusion Zone	Coagulated Grains of Ferrite plus Pearlite
-30° C		
Microphoto	Weld Metal	Cast Coarse-Grained Dendritic Structure
Microphoto	Beginning of Fusion Zone	Ferrite plus Pearlite, Generally Coarse-acicular martensitic
Microphoto	End of Fusion Zone	Coagulated Grains of Ferrite
-20° C		
Microphoto	Weld Metal	Upper Seam-Ferritic-Pearlitic, columnar Structure, typical for cast non-heat treated steel. Porous strongly differentiated pearlite. Lower Seam- Homogeneous Fine-grained ferritic-pearlitic, typical for normalized steel. The pearlite is lamellar.

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(1)	(2)	(3)
Microphoto	Heat Affected Zone	Ferritic-pearlitic in immediate proximity to seam; large grains of pearlite of the Widmanstätten type, typical for highly overheated structure; pearlite somewhat differentiated. Size of pearlite grain diminishes with distance from seam, and in the zone adjacent to basic metal, the grains are practically dots; in this zone the structure is somewhat straited.
×18 C Microphoto	Weld Metal	Upper Seam-ferritic-pearlitic, columnar, typical cast structure. Pearlite somewhat differentiated. Lower Seam-fine-grained ferritic-pearlitic, typical for normalized steel.
Microphoto	Heat Affected Zone	In immediate proximity to seam-ferritic-pearlitic, typical for Widmanstätten structure, with pearlitic differentiated. With distance from seam-very fine-grained ferritic-pearlitic, pearlite, in spots, spheroidized.
Microphoto	Basic Metal	Ferrite-Pearlite

Table 36. Welded Microsections From SKhL-2 Steel, OMM-5 Electrodes Used.

/Follow same headings as in Figure 35, see next page/

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(1)	(2)	(3)
-40° C		
Microphoto	Weld Metal	When mildly pickled, considerable micro-porosity is evident. General cast structure outlines.
Microphoto	Beginning of Fusion Zone	Ferritic-pearlitic, general martensitic trend.
Microphoto	End of Fusion Zone	Coagulated ferritic-pearlitic grain.
-30° C		
Microphoto	Weld Metal	Coarse cast dendritic structure
Microphoto	Beginning of Fusion Zone	Coarse-grained ferrite plus pearlite, with general martensitic trend.
Microphoto	End of Fusion Zone	Coagulated ferritic-pearlitic grains.
-20° C		
Microphoto	Weld Metal	Upper seam-columnar ferritic-pearlitic, typical cast steel structure; the pearlite is porous. Lower seam-fine-grained ferritic-pearlitic typical for normalized steel.

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(1)	(2)	(3)
Microphoto	Heat Affected Zone	In immediate proximity to seam- ferritic-pearlitic, Widmanstätten type; pearlite sharply differentiated. In immediate proximity to basic metal- fine-grained ferritic-pearlitic, typical for re-crystallized structure.
+18.4° C Microphoto	Weld Metal	Upper Seam-columnar ferritic-pearlitic; pearlite is porous Lower Seam- homogeneously distributed very fine ferritic-pearlitic grains; structure typical for normalized steel.
Microphoto	Heat Affected Zone	Ferritic-pearlitic, with pearlite strongly differentiated.

Table 37. Welded Microsections from St. 3 Steel [Same headings].

-40° Microphoto	Weld Metal	Columnar ferritic-pearlitic, typical for cast steel structure.
Microphoto	Heat Affected Zone	Ferritic-pearlitic; pearlite is medium-grained, lamellar; with distance from seam, pearlite grain diminishes in size, Widmanstätten structure.

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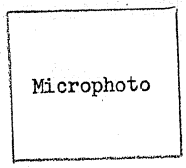
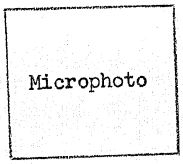
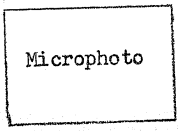
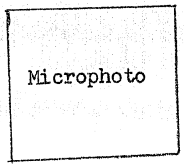
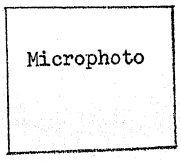
(1)	(2)	(3)
-20° C		
 Microphoto	Weld Metal	Columnar ferritic-pearlitic, typical for cast steel structure.
 Microphoto	Heat Affected Zone	In immediate approximation to seam-ferritic-pearlitic, with pearlite lamellar; with distance from seam, pearlitic grains diminish in size; Widmanstätten structure.
-10° C		
 Microphoto	Weld Metal	Columnar ferritic-pearlitic, typical for cast steel.
 Microphoto	Heat Affected Zone	Ferritic-pearlitic; pearlite is lamellar; with distance from seam, pearlite grains diminish in size.
+18.4° C		
 Microphoto	Weld Metal	Columnar ferritic-pearlitic, typical cast steel structure.
Microphoto	Heat Affected Zone	Ferritic-pearlitic, Widmanstätten type; in immediate proximity to basic metal, the grain structure is finer.

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(1)	(2)	(3)
Microphoto	Basic Metal	Ferritic-pearlitic line structure

Table 38. Welded Microsections from Grade 50 Steel. /Same headings/

-40° C		
Microphoto	Weld Metal	Upper seam-columnar ferritic-pearlitic, typical cast steel structure; pearlite is porous and strongly differentiated. Lower seam-homogeneous fine-grain ferritic-pearlitic, typical for normalized steel; pearlite is lamellar.
Microphoto	Heat Affected Zone	Coarse-grained pearlite edged with ferritic lattice; pearlite is fine-lamellar, typical for over-refined steel. With distance from seam, size of grain is diminished, and, in the basic metal is fine-grained punctate.
-20° C		
Microphoto	Weld Metal	Upper seam-columnar ferritic-pearlitic, typical cast steel structure, with pearlite differentiated. Lower seam-homogeneously distributed fine grain, typical for normalized steel.
Microphoto Microphoto	Heat Affected Zone	In immediate proximity to seam-very coarse-grained compact, almost sorbiticpearlite, edged by ferritic lattice typical for over-refined steel. With distance from seam, size of grain is diminished, and, in zone adjacent to basic metal, is very fine-grained; typical for re-crystallized steel.

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-10°C

Microphoto	Weld Metal	Structure analogous with same at -20 degrees Centigrade.
	Heat Affected Zone	Structure analogous with same at -20 degrees Centigrade.

+18.4° C

Microphoto	Weld Metal	Upper seam-columnar ferritic-pearlitic, typical for cast steel, with pearlite differentiated, but with some pearlite grains compact fine-lamellar.
Microphoto	Weld Metal	Lower seam-fine-grained ferritic-pearlitic, typical for normalized steel.
	Heat Affected Zone	Coarse-grain pearlite, edged by ferritic lattice; the pearlite is fine-lamellar. Typical for over-refined steel. With distance from seam, size of grain is diminished, and in the basic metal it is fined-grained, practically punctate.
Microphoto	Basic Metal	Ferritic-pearlitic, with the pearlite lamellar.

As can be seen from the micro-examination, the structure of the welded seam and the heat affected zone in St. 3 low carbon steel, does not change with relation to the surrounding welding temperatures within the range of plus 18.4 degrees Centigrade to minus 40 degrees Centigrade.

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As a result of the micro-examination of T-welded joints, it was established:

(1) The weld metal of welded joints in SKhL-2 steel welded under minus 30 degrees and minus 40 degrees surrounding temperature has a cast dendritic structure of coarse composition. With an increase in the surrounding temperature (to minus 20, minus 10, zero degrees), the microstructure of the weld metal approximates more and more the ferritic-pearlitic structure.

(2) The microstructure of the fusion zone in SKhL-2 steel joints depends on the surrounding welding temperature to a still greater degree than the weld metal.

It was established that under surrounding temperatures of minus 30 and minus 40 degrees, in welding SKhL-2 steel, the beginning of the fusion zone is coarse-grained with a general trend toward coarse acicular martensitic structure. The end of the fusion zone has a coagulated grain ferritic and pearlitic structure. In other cases, there is ferrite and pearlite, with a general trend toward martensitic structure.

Cracks were observed in SKhL-2 steel specimens that were T-welded under low surrounding temperatures.

(3) The micro-structure of welded joints in SKhL-2 steels varies with relation to the thickness of the plate. With the increase in the thickness of the welded plates, the structure of the fusion zone becomes more stress-concentrated.

(4) In the welding of SKhL-2 steels under low surrounding temperatures, there are more pronounced transitions in the structures of the

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basic metal and the heat affected zone than in the welding of the same steels under conditions of room temperature.

(5) Micro-examinations show that in the welding of SKhL-2 steels with a 0.5 percent carbon content under low surrounding temperatures, sub-hardening occurs in the heat affected zone.

(6) In welding SKhL-2 and Grade 50 steel, it is necessary either to reduce the cooling rate by pre-heating, or to use austenitic electrodes, insuring thereby the maximum plasticity in the weld metal.

(7) Tests have shown that the use of OMM-5 electrodes in the welding of SKhL-2 and Grade 50 steels results in the formation of cracks. Therefore, the above electrodes are not to be recommended for the above use. H. H. Rykalin and L. A. Fridlyand(56) point to the same.

(8) Data obtained by micro-examinations fully concurs with hardness measurements. In the weld metal zone, typical cast metal micro-structures of low hardness prevail; then follows the zone of greater hardening (in SKhL-2 and Grade 50 steels).

Beyong the heat affected zone, the initial ferritic-pearlitic structure of continuous hardness (the basic metal) begins.

(9) In welding SKhL-2 and Grade 50 steel under plus 10 degrees surrounding temperature, also under room temperatures, the structure of the upper layer (when double-layer welded) is a typical cast metal structure, while the bottom layer conforms to the structure of normalized steel.

A columnar microstructure is sometimes in evidence in the upper part of the seam near the fusion boundary where the cooling rates are at their maximum.

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(10) In welding low carbon steels, the micro-structure of the weld metal, the heat affected zone, and the basic metal, do not change, with relation to the surrounding welding temperature, within the range of from minus 40 degrees Centigrade to room temperature.

Chapter VI

THE IMPORTANCE OF THE COOLING RATE IN WELDING

Results of experiments have shown that in order to obtain high-quality welded joints, when welding is performed under low surrounding temperatures, it is necessary to take into consideration several factors out of which, in the case of SKhL-2 and Grade 50 steels, the micro-structure of the heat affected zone, which is tied in with the cooling rates for this zone, is essential.

The cooling rates observed in welding under surrounding frost are more rapid than those in welding under normal temperature. Therefore, the problem relating to the structural components in steels welded under surrounding frost is very essential.

To prevent the formation of undesirable structures in the heat affected zone, it is necessary to know the relationship of the cooling rate at a given surrounding temperature to the welding procedure. With this purpose in view, determinations of the momentary cooling rate at a given temperature were made from equations derived by N. N. Rykalin(54). Let us consider two cases.

(1) Beading-On fillet onto an object having a considerable thickness. In this case, the equation expressing the process of heat convection will be

$$T = \frac{q}{2\pi\lambda\gamma vt} e^{-\frac{z^2}{4at}} \qquad (1)$$

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(2) Butt-welding of thin plates.

$$T = \frac{q}{v\delta\sqrt{4\pi\lambda c\gamma t}} e^{-\frac{y^2}{4at}}, \quad (2)$$

where q is the intensity of the source of heat in calories per second;

v is the arc travel speed in centimeters per second;

δ is the thickness of the plates in centimeters;

λ is the coefficient of thermal conductivity in calories/centimeter second degrees Centigrade;

c is the thermal capacity in gram-calories degrees Centigrade;

γ is the specific gravity in grams per cubic centimeter;

t is the time of the beginning of heating, in seconds, counted off from the moment the arc and the element of the heat affected zone are in the same transverse plane of the metal;

$a = \frac{\lambda}{c\gamma}$ is the coefficient of temperature conductivity in centimeters per second;

T is the temperature of the contemplated element on the travel axis of the source of heat;

y is the radius vector in centimeters;

z is the coordinate.

Let us establish the functional relationship $\frac{\partial T}{\partial t} = f(T)$, i.e. the conformity between the cooling rate and the temperature in the heat affected zone, as per N. N. Rykalin.

For simplification, we will derive this relationship only for points on the axis proper of the seam.

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As per investigations by N. N. Rykalin, the weld cooling rates at a given temperature, for points on the axis proper of the seam, are little different from the weld cooling rates at the same temperature, of points in the heat affected zone.

For the seam axis, let us assume that in equation (1) z = 0, and in equation (2) y = 0.

Then, the temperature will equal:

(1) for the axis of the fillet beading on a thick object:

$$T = \frac{q}{2\pi\lambda\gamma vt};$$

(2) for the butt-welded seam axis in thin plates:

$$T = \frac{q}{v\delta\sqrt{4\pi\lambda c\gamma t}}.$$

The momentary cooling rates will equal for case 1:

$$\frac{\partial T}{\partial t} = -\frac{q}{2\pi\lambda\gamma vt^2}; \qquad (3)$$

And for case 2:

$$\frac{\partial T}{\partial t} = -\frac{q}{2v\delta\sqrt{2\pi\lambda c\gamma t^3}}. \qquad (4)$$

The weld cooling rates are given in the form of a function of time.

For any given moment of time, the temperature can be computed, and the conformity between $\frac{\partial T}{\partial t}$ and T established.

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Therefore, by eliminating time t, we derive a direct ratio between the momentary cooling rate and the momentary temperature for case 1:

$$\frac{1}{t} = \frac{2\pi\lambda\gamma v T}{g}$$

and for case 2:

$$\frac{1}{\sqrt{t}} = \frac{v\delta\sqrt{4\pi\lambda c\gamma}\,T}{g} .$$

Substituting the values $\frac{1}{t}$ and $\frac{1}{\sqrt{t}}$ into equations (3) and (4):

$$\frac{\partial T}{\partial t} = -\frac{g}{2\pi\lambda\gamma v}\,\frac{(2\pi\lambda\gamma v)^2 T^2}{g^2} = -\frac{2\pi\lambda c\gamma v T^2}{g} ;$$

$$\frac{\partial T}{\partial t} = -\frac{g}{2v\delta\sqrt{4\pi\lambda c\gamma}}\,\frac{v^3\delta^3(4\pi\lambda c\gamma)^{3/2}T^3}{g^3} = \frac{v^2\delta^2 4\pi\lambda c\gamma T^3}{2g^2} =$$

$$-2\pi\lambda c\gamma\,\frac{T^3}{(g/v\delta)^2}$$

Thus, the weld cooling rates for the seam axis, or beaded fillet, will equal in case 1:

$$\frac{\partial T}{\partial t} = -2\pi\lambda\gamma\,\frac{T^2}{g/v} ; \qquad (5)$$

and in case 2:

$$\frac{\partial T}{\partial t} = -2\pi\lambda c\gamma\,\frac{T^3}{(g/v\delta)^2} , \qquad (6)$$

where T is the momentary temperature, at the given moment, at the given point, in the process of convection of heat from the welding

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arc, counted off from [the moment] of the initial temperature T_0 of the object being welded.

However, equations (5) and (6) do not account for the pre-heating of the object, which is important, since special steels are frequently preheated prior to welding, with a resulting considerable reduction in the weld cooling rate.

In equations (5) and (6), let us express temperature T in degrees Centigrade and interpolate the [initial] temperature T_0 of the object. Then, the weld cooling rates, for the case of beading a fillet onto a thick object, will be expressed by the following equation:

$$\frac{\partial T}{\partial t} = 2\pi\lambda\gamma\frac{(T - T_0)^2}{q/v} \qquad (7)$$

and for the single pass butt-weld in thin plates:

$$\frac{\partial T}{\partial t} = 2\pi\lambda c\gamma\frac{(T - T_0)^3}{(q/v\,\delta)^2} \qquad (8)$$

where T is the temperature in the process of heat convection from the arc. In the computation, it is substituted by the temperature value of the sub-critical interval. T_0 is the initial temperature of the object to be welded. In our case, T_0 = -40 degrees Centigrade.

When object is pre-heated, i.e. T_0 is increased, the analysis of equations (7) and (8) shows that the cooling rate is considerably decreased.

From equations (7) and (8), it follows that the weld cooling rate depends on:

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(a) the momentary temperature value T;

(b) the effective running heat input q/v;

(c) the size of the object to be welded;

(d) the pre-heat temperature T_0.

The higher the difference between the momentary and the initial temperatures, the more rapid the weld cooling rate. Preheating reduces the weld cooling rate in thin objects to a higher degree than in thick ones. It also follows from equations (7) and (8) that with the lowering of the surrounding temperature, the weld cooling rate goes up considerably.

At the basis of hardening and other types of heat treatment of steels is the relation between the cooling rate and micro-structure. Recent progress in metallography makes it possible to establish, with approximation, the same relation for the welding cycle.

One of the simple, though approximate, methods for establishing the above indicated relation is based on a plane surface test. Over a cycle of micro-structures, taken at various points along the generatrix of the plane surface test specimen, which underwent a special hardening process, an experimental curve $\frac{\partial T}{\partial t}\Big/ T$ curve, is superimposed.

The juxtaposition of the mean cooling rate within the critical temperature interval for any point in the specimen, with the micro-structure and hardness at the same point, furnishes the necessary computation data.

The theoretical method of utilizing the S-curve for the determination of the critical cooling rate and the supercooling temperature

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of austenite, under conditions of a fixed cycle of continuous cooling, was proposed by the Soviet scientist S. S. Shteinberg(57). According to Shteinberg, the process of continuous cooling, as expressed by T = f(t)-curve, is considered to be a summation of the elementary processes of isothermic dissociation with a duration dt. The stability of austenite at temperature T is characterized by the duration of the incubation period .

To each element of time dt, during the continuous cooling, dt corresponds the passing portion of the incubation period $\frac{dt}{\tau}$, at temperature T. In the summation of the consecutive series of such ratios, it will occur, at a certain moment of time, that the entire incubation period has passed, the first nuclei of the transformation of austenite have appeared, and dissociation has set in.

This moment arrives when the summation of the elementary ratios $\frac{dt}{\tau}$ becomes equal to 1:

$$\int_{t_1}^{t_2} \frac{dt}{\tau} = 1$$

where t_2 is the moment in time to which the moment of passing of the entire incubation period corresponds.

This method of computation results in adequate precision, but is highly laborious.

With cooling rates approximating the critical, the duration of the continuous cooling dissociation is by 50 percent greater than the minimum duration of isothermic cooling dissociation, and the temperature is lower by 55 degrees Centigrade. In addition to that, the duration of the dissociation of coarse-grained austenite is twice

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that of the minimum duration of the dissociation of fine-grained austenite.

Yet, the juxtaposition of cooling curves with S-curves, as a practical method for the determination of the welding procedure for a steel of a given micro-structure, is inconvenient on account of its complexity.

There is a simplified method for the determination of the cooling cycle effect upon the micro-structure in welding. In place of the complete cooling cycle, only a part of it, within the sub-critical interval of temperatures, is interpolated into the computation. In so doing, it is assumed that if, with this temperature interval having been passed, the austenitic formation was not dissociated, the probability of pearlitic transformations, under the effect of the welding procedure is negligible, and, as a rule, there is the formation of martensite.

With relation to the anticipated micro-structure, two empirical formulas for the computation of the cooling rate are submitted.

(a) To insure pearlitic transformations, it is imperative that

$$w_1 = \frac{T_1 - (Tm - 55 \text{ degrees Centigrade})}{3t_{min}}$$

where w_1 is the maximum permissible cooling rate;

T_1 is the temperature corresponding to the critical point Ar_1;

Tm is the temperature, under the effect of which the duration of austenitic dissociation is at its minimum; it is determined by the S-curve for the given steel;

T_{min} is the time of the complete dissociation of austenite at temperature T.

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TABLE 39

SAFE COOLING RATES FOR VARIOUS STEELS

Steel	Chemical Composition C	Mn	Cr	Mo	T_l	T_m - 55 degrees Centigrade	ω, in degrees per second	ω_2, in degrees per second
Carbon	0.31	0.46	--	--	720	510	42.5	1.95
Carbon	0.54	0.46	--	--	720	510	33.4	0.898
Carbon	0.78	0.36	--	--	720	510	17.6	0.398
Carbon	0.5	0.91	--	--	720	495	16.7	0.62
Manganese	0.64	1.13	--	--	720	510	3.8	0.30
Manganese	0.65	1.32	--	--	710	484	2.13	0.148
Manganese	0.35	1.85	--	--	700	425	1.39	0.5
Molybdenum	0.42	0.2	--	0.21	725	455	6.5	1.85
Molybdenum	0.40	0.42	--	0.52	725	590	0.0090	0.75
Molybdenum	0.36	0.17	--	0.82	725	620	0.012	0.795
Molybdenum	0.33	0.41	--	0.96	725	620	0.0018	0.64
Chromium	0.37	0.37	0.57		725	620	2.23	0.90
Chromium	0.42	0.68	0.93	--	735	590	1.2	0.658
Chromium	0.32	0.45	1.97	--	765	635	0.176	0.612

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(b) Martensite is not formed in the case when austenitic transformation has been completed at temperature T = 350 degrees Centigrade.

To insure this, it is imperative that

$$\omega_2 = \frac{T_1 - 350 \text{ degrees Centigrade}}{3t'}$$

where t' is the time of austenitic dissociation at 350 degrees Centigrade.

When the cooling rates have the ω_2-values, the micro-structure may be sorbitic, troosto-sorbitic, or troostitic.

The safe cooling rates ω_1 and ω_2 for various steels were computed, and they are given on the following page in Table 39.

The juxtaposition of the kinetics of austenite dissociation with the welding thermal cycle is adequately reliable and universally accepted as a method for the analysis of the micro-structure of the basic metal in welding.

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I. MARTENSITE TRANSFORMATION

The acceleration of the cooling rate, particularly below the martensitic point, reduces the amount of retained austenite, or, in other words, promotes martensitic transformation. At room temperature, the martensitic transformation in carbon steel (0.6 percent carbon) is not yet complete, and it continues with cooling below zero, down to minus 140 degrees Centigrade.

Rapid cooling for obtaining martensitic hardening is necessary only for the purpose of supercooling austenite across the zone of its least stability (600 to 500 degrees Centigrade), and of preventing its transformation into troostite. As to martensite transformation, it takes place both under maximum and minimum cooling rates.

The martensitic point Ar'' (M) is not predicated on the cooling rate, but is determined by the degree of concentration in the solid solution of γ-iron, of alloying elements (carbon in the case of carbon steels). The above point M becomes lower with the increase in carbon content, as a result of which the amount of retained austenite, at room temperature, increases alongside of the increase in carbon content.

Rapid cooling, particularly under frost conditions, reduces the amount of retained austenite in hardened steel, in other words, it promotes the transformation of austenite into martensite.

Martensite transformation takes place with the maximum supercooling of austenite (below 400 degrees Centigrade), when only the displacement of atoms in the iron lattice, and the transition of γ-iron into α-iron, without the segregation of carbon or cementite, occurs.

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In martensite transformation, no diffusion occurs, and the reconstruction of the iron lattice takes place instantaneously with no diffusion period.

This transformation occurs so rapidly that even a super-speed motion picture camera cannot detect the instantaneous formation of the martensitic needle(58).

It is known that in order to impart certain characteristics to steels some special admixtures, such as chromium, nickel, tungsten, molybdenum, copper, vanadium, and others are added, or the amounts of conventional ingredients, such as silicon and manganese, are increased. Alloy steels in welding manifest a microstructure which is different from structures generated in the welding of conventional low carbon steels. The above mentioned admixtures, as a rule, increase the hardenability of steel, i.e. increase the stability of austenite by retarding and inhibiting the dissociation process in cooling(59). Very frequently, in the welding of alloy steels, the formation of martensite occurs in the weld metal and in the heat affected zone.

In welding under surrounding frost, as mentioned above, the cooling rate is accelerated considerably, as compared with the cooling rate of welding under room temperature, with the result that the probability of martensite formation in the weld metal and the heat affected zone is also increased.

As related to the cooling rate, various modifications of martensite are derived. The martensite derived under conditions of a retarded temperature reduction is not as hard and brittle as the martensite formed under conditions of rapid cooling. In the latter case, with insufficiently fine grain, microscopic cracks are manifested.

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Volumetric changes, due to the fact that under very rapid cooling at the moment of martensite formation the metal suddenly expands, may, in a rigid medium, lead to the formation of cracks. The excessive hardness in the martensitic zone may be completely, or partially, eliminated by subsequent heat treatment. There is, however, no treatment of any kind for cracks that have occurred.

The basic effect of the majority of alloying admixtures and carbon consists in that they can induce hardening even during air-cooling.

The positive effect of alloying elements, in the opinion of many specialists(60), is manifested in some high strength, non-hardened structural steels for buildings which were welded without following any particular precautionary procedures. In such cases, the steel is to live up to specifications of greater strength than carbon steel is capable of delivering after slow cooling. In this case, it is imperative that the steel retains high ductility after rapid cooling.

In high carbon steel, containing chromium and manganese (the latter in amounts higher than normal), the transformation of austenite into martensite is usually incomplete. In hardening, some quantity of non-stable austenite is unavoidably retained, even after most of the austenite has been transformed into martensite by the use of special cooling.

The amount of the retained austenite may reach 10 to 25 percent. In heating to the required temperature, the retained austenite will dissociate in conformance with the characteristics of the isothermic transformation for the given steel. In some cases, cooling to a low

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temperature causes a partial dissociation of the retained austenite, at times accompanied by the formation of cracks.

The retained austenite usually dissociates at around 200 degrees Centigrade, and the product of this dissociation is not martensite, which possesses a high degree of hardness, but bainite, distinguished by a somewhat higher degree of hardness, as compared with the hardness of martensite, tempered at the same temperature.(60)

The normal /normalizing?/ temperature for steels with an adequate content of carbon and alloying elements is not yet the end of martensite transformation. Through subsequent cooling, the suspended process of martensite transformation is resumed: the retained austenite is transformed into martensite, with a consequent change in the characteristics of the steel, such as the appearance of greater hardness, increase in size, higher cutting characteristics in tools, etc.

When considering low alloy steels with a carbon content up to 0.5 percent and a total of alloying elements up to 3 percent (by the microstructure, these are structural steels of the pearlitic class), we see that one of the basic difficulties in the welding of these steels is the formation of hardenability structures in the heat affected zone(54).

The hardening in the heat affected zones is tied in with the supercooling of the solid solution of austenite. With high cooling rates, under conditions of frost, there isn't enough time for the austenite to become dissociated at the temperature which corresponds to the given composition of the steel with relation to the iron carbon equilibrium diagram, and it continues to exist at considerably lower temperatures. The supercooled austenite continues for some time in

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its characteristic of stability. Upon the elapsing of a certain amount of time, known as the incubation period, the austenite becomes dissociated, with the formation of sorbitic, troostitic, and martensitic microstructures.

With the deep freezing of austenite, the crystallographic lattice of the gamma-iron is momentarily reconstructed into an alpha-iron lattice with insufficient time for the carbon atoms to segregate so that they remain embedded in the alpha-iron lattice. Thus, martensite is a constrained solid pseudo-solution of carbon in alpha-iron.

The transformation of austenite into martensite is accompanied by a volumetric increase: of all components, martensite has the lowest specific gravity (7.58 grams/cubic centimeter), and ferrite the highest (7.85 grams/cubic centimeter).

The obtaining of a martensitic structure is the purpose of heat treatment, although, in the welding of pearlitic steels, martensite is undesirable, since it has hardness and strength, but not ductility.

In the welding of pearlitic steels, martensite is formed in the heat affected zone only, which circumstance frequently results in the formation of cracks. This zone, martensitically hardened, tends to expand, but this local expansion is restrained by the mass of the basic metal. As a result of this struggle, internal stresses develop in the heat affected zone, which, in the case of low plasticity in the metal, will result in the formation of cracks.

In the process of martensite transformation, coarse grains of martensite are formed in the coarse grains of austenite at their sliding surfaces. Since the process of martensite formation is very rapid,

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considerable internal stresses may appear, leading to buckling and even to cracking.

In the case of fine-grained austenite, the process of plastic deformation at the multitude of sliding surfaces of the fine grains runs a much smoother course, and the resulting martensite is less stress concentrated. Coarsened grains lead to the appearance of hardenability cracks.

II. HARDNESS OF THE WELDED SEAMS AND THE HEAT AFFECTED ZONES IN WELDING UNDER LOW SURROUNDING TEMPERATURES.

The problem of hardness in the weld metal and the heat affected zone is of great practical importance, since the hardening of the heat affected zone very frequently reduces the deformation capacity of welded joints, promoting the formation of cracks and impeding subsequent machinability.

The connection between the cooling rate and hardness (type of microstructure) for a given steel may be determined either by a plane surface test for hardenability, or by a fillet test, as per the MVTU [Moscow Technical College] method.

The test by the MVTU method consists in beading-on fillets onto specimens from test steels under welding procedures characterized by various magnitudes in the running weld heat input of the welding arc.

The plane surface test shows the ratio between the cooling rate of a point in the specimen, within a definite temperature interval, and also between the hardness of this point, and the distance to the end, which is cooling off.

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The MVTU method, developed by N. N. Rykalin and L. A. Fridlyand[56], results in more flexible and effective indexes than the plane surface test.

Its advantages are as follows:

(a) Determination of the tie-in between the cooling rate and hardness by the MVTU test takes place under actual welding conditions, while in the plane surface test, the temperature of the specimen is different from that of the heat affected zone, and, therefore, their structures, while being of the same hardness, may differ.

(b) In the MVTU test, the cooling rates for the metal are easily controlled, and the cooling rate values are computed analytically, as well as the cooling rates for the heat affected zone in welding.

(c) The MVTU test can be made on steel of any thickness.

The hardness and microstructure of the heat affected zone determine, to a considerable degree, the plasticity of the welded seam and its dynamic strength.

The structure and hardness of the heat affected zone of a given steel, upon being heated by the welding arc and upon subsequent cooling, are determined mainly by the cooling rate within the sub-critical temperature interval.

To determine the effect of low temperatures on hardness, we will analyze equation (8) for various surrounding temperatures in the welding of one of the specimens from SKhL-2 steel; δ = 10 millimeters = 1 centimeter. Welding cycle is as follows:

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v = 0.4 centimeter/second; I = 240 amperes; U = 25 volts; η_u = 0.7; λ = 0.097 calories/centimeter per second degrees Centigrade; $C\gamma$ = 1.3 calories/centimeters^3 degrees Centigrade.

N. N. Rykalin suggests that when the sub-critical temperature interval for a given grade of steel is not known, it should be assumed for computation purposes that T = 600 degrees Centigrade, since, for all steels of the pearlitic class, these temperature intervals lie within the range 720-480 degrees Centigrade, and the computation error will be small.

The temperature for the least duration of the dissociation of austenite in SKhL-2 steel can be taken as equal to 530 degrees Centigrade(56). Consequently, T = 530 degrees Centigrade; T_0 = -40 degrees Centigrade.

The momentary cooling rate is:

$$\frac{\partial T}{\partial t} = -2\pi\lambda c\gamma \frac{(T - T_0)^3}{(q/v \times \delta)^2}$$

Substituting the numerical values, when q = 0.24 x 0.7 x 240 x 25 = 1008 calories/second.

When T_0 = -40 degrees Centigrade:

$$\frac{\partial T}{\partial t} = -2 \times 3.14 \times 0.097 \times 1.3 \frac{[530-(-40)]^3}{\left(\frac{1008}{0.401}\right)^2} = 29 \text{ degrees/second}$$

When T_0 = -30° degrees Centigrade:

$$\frac{\partial T}{\partial t} = -2 \times 3.14 \times 0.097 \times 1.3 \frac{[530-(-30)]^3}{\left(\frac{1008}{0.411}\right)^2} = 27 \text{ degrees/second}$$

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When T_0 = +20 degrees Centigrade:

$$\frac{\partial T}{\partial t} = -2 \times 3.14 \times 0.097 \times 1.3 \frac{(530-20)^3}{\left(\frac{1008}{0.411}\right)^2} = 21 \text{ degrees/second}$$

On the momentary cooling rates curve for plane surface test specimens (Figure 47), borrowed from N. N. Rykalin, we find the following distances in millimeters from the cooling off end:

Cooling Rate in degrees/seconds	Distance From Cooling Off End in Millimeters
29	7
27	8
21	11

And by the curve graph of hardness for SKhL-2 steel (Figure 48), we locate the hardness corresponding to the above distances:

Distance in Millimeters	Hardness H_B (Vickers)
7	330
8	310
11	280

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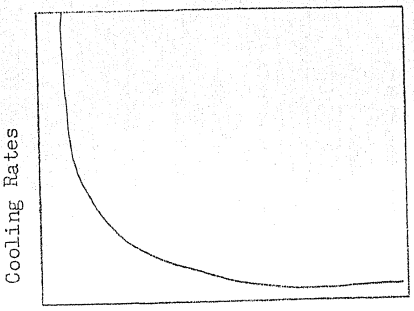

Figure 47. Momentary Cooling Rates Curve.

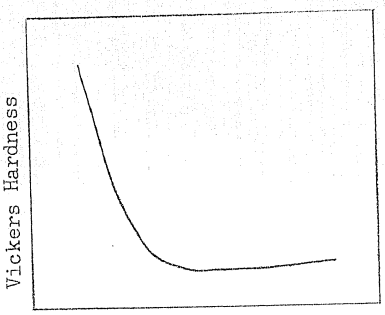

Figure 48. Hardness Curve for SKhL-2 Steel.

N. N. Rykalin thoroughly investigated the hardenability of the heat affected zone in SKhL-2 steel, and, having plotted the above curve graphs, he reports that at the distance of 8 to 9 millimeters from the cool-off end of the specimens, a gamma-iron structure is observed with the following order of sequence:

(a) coarse-acicular martensite with troostite, the amount of the latter increasing gradually with distance from the end.

(b) Troostosorbite with retained martensite.

(c) Coarse-grained sorbite with small areas of troostite.

(d) Coarse grains of weakly differentiated sorbite.

(e) Coarse-grained Widmanstätten ferritic-pearlitic structure, almost continuous through the specimen, beginning with 12 to 13 millimeters from cool-off end.

Thus, it can be assumed that the heat affected zone in SKhL-2 steel, welded under a surrounding temperature of minus 40 degrees,

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was hardened to H_v = 330, the hardness of the basic metal being around H_v = 200.

The above pertains to single layer seams.

In the multiple layer welding of SKhL-2 steels (in our case, 2 layer), the heat affected zone either does not harden at all, due to the periodic heat supply to the metal, or becomes tempered from the high temperatures, as a result of which its hardness is considerably reduced.

Our tests confirmed the data submitted by N. N. Rykalin on the hardenability of the heat affected zone in SKhL-2 steel, also in the case of low temperatures. In the case of extreme hardening in the heat affected zone for a given brand of steel, it is useful to decrease the cooling rate by pre-heating.

To reduce the cooling rate, it is necessary to increase the running weld heat input by changing the welding procedure in the direction of reducing its speed, which, /however/, is not expedient. This is why pre-heating is more rational.

Knowing the cooling rate for the heat affected zone, and disposing of the MVTU test curves plotted for the particular grade of steel at hand, the a priori determination of hardness and microstructure in the heat affected zone becomes possible without conducting actual welding tests.

The following deductions can be made from the above:

(1) With the reduction in surrounding temperatures, the cooling rates in welding are increased, which in turn increases the hardness

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of the metal in the heat affected zone.

(2) The computation premises for the selection of welding procedures, as developed by N. N. Rykalin, make it possible to control the process by welding procedure parameters and by the temperature cycle of cooling, which /together/ determine the microstructure in the heat affected zone, and, by virtue thereof, the mechanical characteristics of the welded joint.

CONCLUSION

The above welding tests, conducted under conditions of low surrounding temperatures, allow the following deductions to be made:

(1) Welded joints effected under low surrounding temperatures, and tested in tension at plus 18.4 degrees Centigrade, showed an increase in ultimate strength with further reduction in the surrounding temperature of welding. The ultimate strength of the welded seam is increased by 3 to 10 percent in SKhL-2 steel, and to an insignificant degree in St. 3 steel. The maximum increase in ultimate strength, by 9 to 17 percent, is registered for Grade 50 steel.

(2) Welded joints effected under low surrounding temperatures, and tested in tension at minus 40 degrees Centigrade, show an increase in ultimate strength of 4 to 10 percent, as compared with the test indexes obtained at room temperature.

It is to be noted that the ultimate strength indexes for welded seams in SKhL-2, St. 3, and Grade 50 steels, which were effected with the use of TsL-5 electrodes, are higher than those effected with the use of OMM-5 electrodes.

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(3) Welded joints in all the test steels effected under low surrounding temperatures, and tested at plus 18.4 degrees Centigrade for bead, show somewhat reduced angles of bead.

However, the angles of bead for welded seams in SKhL-2 steel effected under a surrounding temperature of minus 40 degrees were equal to 75 to 116 degrees.

Still higher values for the angle of bead were observed on welded seams in St. 3 steel, with the exception of seams effected under minus 40 degrees, in which case their values were somewhat smaller than the same in SKhL-2 steel.

Angles of bead, within the range of 40 to 75 degrees, were observed on the welded seams in Grade 50 steel.

At a test temperature of minus 40 degrees, the angle of bead is approximately half the size of what it is at normal temperature.

(4) With the lowering of the surrounding temperature under which welding is done, the impact ductility of the welded seams at the test temperature of plus 18.4 degrees Centigrade for all grades of steel becomes reduced.

In SKhL-2 steel, it is reduced by 7 to 37 percent, in St. 3 steel by 5 to 22 percent, and in Grade 50 steel by 10 to 15 percent.

However, the impact ductility indexes for welded seams in SKhL-2 steel, effected under minus 40 degrees Centigrade, are still adequately high, equalling 8 kilograms/per square centimeter.

In impact tests conducted at minus 40 degrees Centigrade, a general drop in impact ductility indexes is observed. For welded

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seams in SKhL-2 steel, effected under normal temperature with the use of TsL-5 electrodes, impact ductility is equal to 3 to 4 kilograms/square centimeter, and for seams effected under minus 40 degrees, it is equal to 1 to 2.5 kilograms/square centimeter.

When, for the same steel (SKhL-2), OMM-5 electrodes are used, impact ductility is reduced to 0.5 kilograms/square centimeter.

For welded seams in St. 3 steel, when TsL-5 electrodes are used, impact ductility is equal to 4 to 5 kilograms/square centimeter, i.e. half as high against the index (7.5 kilograms/square centimeter) obtained at the test temperature of plus 18.4 degrees.

Impact ductility in Grade 50 steel welded seams tested at minus 40 degrees is reduced 3 to 4 times, as compared to the indexes obtained when tested at plus 18.4 degrees.

(5)Metallographic examinations of the microstructure in the weld metal of the welded seams effected under surrounding temperatures of from minus 30 to minus 40 degrees, for all grades, do not show any particular changes, as compared to the microstructure of the weld metal when welding is performed under room temperature.

The only distinguishing feature in the weld metal of the seam effected under low surrounding temperatures is its coarser dendritic structure.

(6) The microstructure at the beginning of the fusion zone is tied in with the acceleration of the cooling rate under the effect of low temperatures, and, in the case of SKhL-2 steel, it is characterized by a sharply stress-concentrated structure, coarse-grained, with a general orientation toward coarse-acicular martensite. With

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the transition to the basic metal, more favorable microstructures (ferritic-pearlitic) are observed.

The microstructure of the fusion zone, in seams effected under low surrounding temperatures, is also related to the thickness of the metal being welded, and, all other factors being equal, becomes more unfavorable with greater thicknesses of the metal to be welded. In some cases, the presence of stresses in the heat affected zone leads to the formation of cracks.

(7) Results of metallographic investigations into the microstructure of welded seams are confirmed by hardness tests. The weld metal zone shows a microstructure which is typical of cast metal and is of low hardness, then follows the hardened zone (in the case of SKhL-2 and Grade 50 steels). The hardness of the heat affected zone, which, in the case of SKhL-2 steel, was additionally air-hardened, equals 220 to 240 H_B, the hardness of the basic metal being 150 H_B.

In the case of St. 3 steel, no additional air-hardening occurs in the heat affected zone.

A sharp hardening of the heat affected zone occurs in Grade 50 steel. It is 300 H_B, with the hardness of the basic metal equal to 150 to 160 H_B.

The weld metal of welded seams effected under low surrounding temperatures is characterized by a hardness that is typical for cast steel.

(8) An X-ray examination of welded seams, effected under low surrounding temperatures, does not disclose any specific changes in the metal of the seam, which could be attributed to the low surround-

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ing temperatures. Only the effects of the grade of electrodes used (TsL-5 or OMM-5) upon the density and continuity of the microstructure can be judged by the results of the X-ray examination.

It is assumed that the X-ray examination may disclose the shortcomings in the quality of the welder's workmanship, /if any/, under low surrounding temperatures, which render the job of the welder difficult. In our case, due to the short work period, the cold, as disclosed by the X-ray examination, did not adversely affect the workmanship.

(9) The theoretical thermal computations for the welding process under conditions of surrounding cold, which were made on the basis of the thesis by N. N. Rykalin, were in full agreement with the computation data derived experimentally.

The experimental heat convection curve graphs conform to those developed by N. N. Rykalin theoretically, and they do not differ considerably between welding under room temperature and under surrounding frost. The effect of the low surrounding temperatures was limited to the fact that the maximum temperatures at points equidistant from the welded seam are lower for welding under frost than they are for welding under room temperature.

On the basis of the obtained computation and experimental data, it is possible to select the most advantageous technological process for welding under low surrounding temperatures with a view to obtaining high mechanical characteristics in the welded joints of high-strength steels of the SKhL-2 type.

(10) Theoretical computations and experimental measurements

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of the thermal state of the metal in the process of welding, confirmed by the metallographic investigation of its microstructure in the heat affected zone, pointed to the possibility of crack formation in cold weather welding, but at the same time made it possible to find counter-measures against it by the selection of suitable welding procedures, pre-heating of the metal, etc.

The tendency to crack formation is increased with the reduction in the surrounding temperature, and, moreover, with the increase in thickness of the objects to be welded.

(11) Measurements for the deformation of plates when beading fillet onto the edge under various surrounding temperatures established the fact that deformation practically does not depend on the surrounding temperature.

It was also established that the use of OMM-5 electrodes in welding under frost (particularly from minus 30 to minus 40 degrees Centigrade) promotes the formation of cracks, while the use of TsL-5 electrodes under analogous conditions is not accompanied by the formation of cracks.

The data obtained also made it possible to arrive at a series of practical conclusions and recommendations which may be useful to industrial plants and construction projects which have occasion to conduct welding operations under winter conditions.

Below are practical suggestions which must be taken into consideration:

(1) Successful welding performance under conditions of frost depends on a thorough development of the technological procedure and

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its strict observance, the efficiency of design of the entire structure and its individual sub-assemblies, careful technical control, and control of the actual operations.

The technological specifications for welding under conditions of frost reduce themselves to two basic positions: first, it is necessary to attain a minimum cooling rate; second, the method of welding must eliminate the possibility of stresses which lead to disintegration.

Rapid cooling is tied in with the appearance of hardened structures in the heat affected zone in structural steels. Welding stresses, combined with the formation of hardened areas, may lead to the development of cracks. In welding objects of considerable thickness, hardenability is more sharply pronounced, and, in combination with volumetric stresses in the metal, it results in a higher degree of brittleness in the welded joint.

It is therefore recommended that, in the welding of objects of great thickness, pre-heating to a temperature of 150 to 200 degrees Centigrade be resorted to in order to obtain a more slow and even cooling rate.

Pre-heating is also effective in the welding of structures in rigid attachment, or of rigid profile, in which cases there is an impedance to free shrinkage deformations.

Pre-heating may be effected with the aid of various devices, such as blow torches, portable roasters, electric induction heaters, etc.

(2) Actual experience, confirmed by experimental research,

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shows, in a series of cases, the feasibility of higher running weld heat input of the welding arc. In welding with an arc of higher heat input, it is not only the ultimate strength and density of the welded seam that become improved, but also its ductility, which is of particular importance in welding under frost conditions. This improvement in the above mentioned values is due to more intensive heating, i.e. a greater amount of heat input by the arc, and a slower cooling rate.

Experiments have shown that in welding steels with a higher carbon content under frost conditions, hardened structures will appear in the heat affected zone. Therefore, when St. 4 steel structures are to be welded under low surrounding temperatures, special technological processes are to be used.

Cold weather welding also calls for the use of electrodes with quality coatings. The electrodes are to conform with specifications as formulated in GOST 2523-44, and must not contain carbon in excess of 0.2 percent.

(3) In line with some constructive requirements, the crowding and crossing of seams is to be avoided.

In the case of crossing of seams which run in different planes, it is necessary at the point of crossing to discontinue one of the seams with the retention of its required computational length.

At the beginning and at the end of the seam, non-fusion occurs. These spots are usually the nuclei of crack formation. It is therefore necessary to tack-weld the ends of the seam to temporary baffle plates, particularly in cold weather welding.

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Structures that were welded under cold weather conditions are to undergo a particularly rigid inspection and quality control.

(4) Cold weather welding (down to minus 40 degrees Centigrade) of type St. 3 steels, with a thickness up to 15 to 20 millimeters, may be conducted without the use of special technological procedure (pre-heating), but pre-heating is to be employed when thicknesses are in excess of 20 millimeters. In the case of SKhL-2 steel, pre-heating is to be employed beginning with thicknesses in excess of 12 millimeters.

Welded joints, effected under conditions of frost, in the above grades of steel, possess adequately high mechanical characteristics in full conformity with specifications for welded seams in responsible structures.

(5) In order to eliminate the possible adverse effect of the physical discomfort of the welder working under conditions of cold weather, upon the quality of the welded seam, the use of electrically-warmed overalls is recommended. Under these conditions, automatic and semi-automatic methods of welding, where the quality of the seam does not depend on the physical comfort of the welder, are of great advantage.

The wide application of alloy steels in the USSR makes it necessary to conduct research pertaining to the welding of these steels under various surrounding temperatures.

THE END

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